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# A Research and Development Strategy for Unexploded Ordnance Sensing

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This technical report has been reviewed and is approved for publication.

FOR THE COMMANDER

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# A RESEARCH AND DEVELOPMENT STRATEGY FOR UNEXPLODED ORDNANCE SENSING

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# ABSTRACT

MIT Lincoln Laboratory has been tasked, by the Strategic Environmental Research and Developmental Program (SERDP), to assist in defining basic and exploratory research and development needs in the area of unexploded ordnance (UXO) sensing. We have recently completed a four-month study whose recommendations and supporting evaluations are documented in this report. We have recommended a systems approach to UXO sensing that emphasizes

— the utilization and integration of existing sensing technologies,

— the investigation of phenomenological concerns associated with different sensors, environmental conditions, and UXO types, and

— the general requirements on data handling, processing, and interpretation.

We have defined a structure in which to initiate and conduct UXO-sensing technology development and, where possible, we have supported our recommendations with analyses and examples from related sensing applications. Our recommendations are intended to serve as a guideline for SERDP in establishing its future research priorities for the challenging task of characterizing and remediating UXO-contaminated lands in the United States.

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# 1. INTRODUCTION

Unexploded ordnance (UXO) represent a significant impediment to the clean-up and re-use of many Department of Defense sites. The standard methodology for the detection of UXO involves laborious ground surveys over potentially contaminated land typically with some form of metal detectors. Probable locations of ordnance are marked, and highly-trained personnel are then required to remove each piece of ordnance that is identified. Typical times for the survey and clearance of UXO-laden areas range from less than one acre to a few acres per day. This methodology is impractical in meeting the timeline for clean-up of vast quantities of DoD land, as mandated in recent federal legislation.

To address this challenge, a number of efforts to explore technologies that can facilitate the detection of UXO have been initiated. Most of these programs have evolved from efforts in mine detection, with contributions from other areas such as buried and obscured-object detection, robotics, automatic target recognition, and chemical sensing. Relevant sensing technologies have included magnetic, gradiometric, and electromagnetic-induction detectors, ground-penetrating radar, electro-optic sensors, airborne synthetic-aperture radar, and nuclear-based sensors. What is clear, even with cursory investigations, is that no single sensor is capable of detecting all ordnance under all conditions, thus researchers must focus their efforts on sensor integration. The challenge lies in designing optimal suites of sensors that meet the DoD user requirements while leveraging the vast amount of resources that have already been invested in this and similar problems. Until now, UXO-sensing research has been fragmented, has focused on demonstrations rather than technology development, and has lacked a unified strategy for addressing the problem.

MIT Lincoln Laboratory has been tasked by the Strategic Environmental Research and Development Program (SERDP), to assist in defining basic and exploratory research and development needs in the area of UXO sensing. To fulfill this task, we have conducted extensive literature reviews of relevant programs both within and outside of DoD, we have spoken to representatives of organizations engaged in UXO-sensing activities, we have spoken to members of national and local-regulatory agencies as well as potential users of converted DoD land, and we have drawn on our own expertise in systems design and sensing technologies. We were also asked to review a few specific programs relevant to UXO sensing. Those programs were the Jefferson Proving Ground Demonstration, the Remote Minefield Detection System (REMIDS), and the Mobile Underwater Debris Survey System (MUDSS).

We have addressed the UXO problem in as broad a sense as possible, asking questions such as "how bad is the problem?", "what information do we need to address the problem?", "what technologies can be brought to bear?", and "how can we best use existing resources?". The results of our efforts are documented in this report, where we recommend a multi-layered research and development program designed to address the UXO-sensing problem. Where possible, we have supported our recommendations with examples from related applications, such as mine detection. We have also attempted to define the underlying science requirements that are critical in designing, integrating, and assessing the performance of UXO-sensing systems. Our recommendations are intended to serve as a guide for SERDP in establishing its future research priorities in the thrust area of clean-up. We also hope that it will be viewed as a resource to other Government agencies facing the difficult task of returning contaminated land to public use.

# 2. EXECUTIVE SUMMARY OF RECOMMENDATIONS

In formulating our recommendations, we have focused on several aspects of the UXO-sensing problem. One aspect is concerned with technology development, i.e., we must identify the most promising sensing tools and how we can structure a research-and-development program to rapidly evolve those tools into useful field instruments. Another aspect is programmatic – contaminated lands must be cleaned up before they can be transferred to the public sector. This requirement applies no matter what the status of the technology development effort and drives both the sensing technologies and the timeline for their development. A third aspect is socio-political and concerns the public's acceptance of lands previously identified as potential UXO hazards. For each of these three aspects, we offer specific and general recommendations that we will summarize in this section.

## 2.1 TECHNOLOGY DEVELOPMENT

The ideal sensor system for UXO detection would have the following characteristics:

- It would offer wide-area, rapid coverage over a variety of terrains representative of UXO-contaminated areas.

- The sensor would locate both surface and buried UXO and be able to positively distinguish ordnance from naturally occurring and man-made clutter.

- The sensor would be able to distinguish inert ordnance from those with explosive potential.

- The sensor's detection and identification capability would be automated and not require human interpretation of imagery.

We feel confident in concluding that, at this time, no single technology will provide all of the aforementioned characteristics. Furthermore, we do not believe that a single comprehensive UXO-sensing system can be constructed that can effectively survey all possible terrains for all possible ordnance types. The UXO problem will not be solved by a single "magic bullet", and we do not recommend devoting a large fraction of the research budget to developing new or experimental technologies that claim to do so.

**We recommend that the best approach to addressing the UXO sensing problem is to develop multiple-sensor systems that make maximum use of the favorable aspects of the UXO problem.**

Multiple sensors are required to address the large variety of conditions under which a UXO-sensing system must operate. Individual sensors should be chosen both for their inherent ability to sense UXOs and for their compatibility in a more capable sensor suite. For example, although one system may offer wide-area coverage, it may not offer buried-UXO-detection capability. Another system may identify explosive ordnance but at speeds too slow to accomodate large-area surveys. The challenge lies in identifying those current technologies that, singly or in groups, can address the comprehensive requirements for UXO sensing.

Consideration of those aspects of the UXO-sensing problem that are favorable for sensor deployment should be a strong factor in choosing the appropriate sensor technologies. For example, most of the potentially contaminated sites are under DoD control; therefore, there is no need for covertness or long-range communication systems. Second, sensing systems can be operated at whatever time of day or season or weather conditions are optimum for the technology.

**Our strongest recommendation is that sensor technology development should be done in accordance with an overall system approach to UXO sensing.**

One of the main purposes of our study is to recommend such a systems approach. Specifically, we propose a four-stage structure for UXO sensing, where the stages function sequentially to reduce the amount of land that requires surveying for UXO, while offering high probability of detection and low probability of false alarm in each sensing stage.

We call the four stages

- Prescreening,
- Cuing,
- Detection, and
- Classification.

The intention of the prescreen stage is to prioritize those lands that require surveying, either because of intended land use or known contamination information, by the degree of urgency that their clean-up mandates. A second goal is to identify those suspect lands that are not likely to contain ordnance or whose intended land use does not require immediate attention. Information for this stage would be obtained, for example, from site records, and historical airplane and satellite imagery. By focusing on both the history and destiny of a site, one can hope to reduce, by a considerable degree, the amount of land that must be addressed for surveying in the near term.

For those lands identified in the prescreen stage as requiring surveying, we suggest a cuing stage that offers rapid coverage, and whose goal is the identification of UXO fields. This sensing stage is most likely to require an airborne platform, and will not target the detection of individual UXO, but rather the clusters and concentrations of UXO representative of testing and training exercises.

Some lands identified during the prescreen stage may bypass the cuing stage altogether, either because of specific information regarding the location of UXO or because of inaccessibility of the terrain to the cuing platform. These lands, together with those identified during the cuing stage as potentially containing UXO fields, would be subject to the next stage of sensing, which we call detection. The goal in this stage is to detect and map locations of individual UXO within the boundaries identified in either the prescreen or cuing stages. The platform for this stage of sensing would most likely be ground or near-ground-based, and the UXO maps would provide the neccessary information for assessing the future use of the land or for initiating the clean-up efforts.

As a final sensing stage, we propose a classification stage whose goal is to distinguish those ordnance that pose a hazard to human safety or the environment from those that are unlikely to explode, which we call nuisance ordnance. One possible implementation of this stage is to interrogate individual ordnance that have been located in the detection stage and provide a secondary map layer that identifies only those that are hazardous. Alternatively, the classification sensors could be integrated onto the detection platform and provide that information concurrently. The motivation for this classification stage is the relatively large payoff that results if all ordnance do not have to be treated as hazardous.

Each of the four stages declares some lands as not requiring immediate attention (which is not quite the same as 'free of ordnance') and passes some lands on to the next stage for more detailed examination. Each of the three sensing stages – cuing, detection, and classification – requires the integration of multiple sensors and the development of data-processing techniques to exploit the complementarity of those sensors.

**In order to best define the individual technical requirements within each sensing stage, we recommend that a detailed systems analysis be conducted of our recommended four-stage approach to UXO sensing.**

Such an anaysis would examine the general and specific requirements for UXO sensing at representative contaminated sites, including considerations such as effectiveness of the sensing technology, ease of sensor deployment, environmental conditions, UXO characteristics, and time requirements for the UXO surveys. On the basis of a preliminary systems analysis, we have identified what we believe are the most likely sensor technologies for each of the sensing stages. Our recommendations, which will follow in detail in subsequent chapters, address both the sensor technologies as well as the concerns related to their integration, deployment, and interpretation.

The critical technical components to be developed within each sensing stage are as follows.

Cuing:

- an airborne platform with onboard differential GPS and INS for accurate navigation and positioning,
- a dual-band (X-band and UHF) synthetic aperture radar (SAR) sensor to detect surface and shallow-buried ordnance,
- an electro-optic sensing system that includes passive detection of two infrared bands and active detection of one visible to near-infrared band for detection of surface and shallow-buried ordnance and clutter characterization.
- sensor-fusion techniques that take advantage of each sensor type's complementarity and unique contributions to the overall system,
- data processing that focuses on identifying clusters or concentrations of "ordnance" signal returns so that ordnance fields, rather than individual ordnance, are identified.

Detection:

- a ground or near-ground-based platform with integrated differential GPS for position marking of suspect ordnance to within 50 cm position accuracy,
- magnetic (gradiometric) sensors for surface and buried ferrous-metallic ordnance detection,
- a ground-penetrating radar sensor for detection of ordnance, rocks, voids, and other clutter,
- sensor and data-fusion algorithms to assist in exploiting the complementarity between the two sensor types.

Classification:

- a ground-based platform that may operate concurrently with or independently of the detection-stage sensing system,

- a thermal-neutron activation sensor that detects the presence of (at least) nitrogen, a primary constituent of explosive materials.

We believe, for the most part, that the current state-of-development of the sensor technologies that we recommend is adequate for the task of UXO-sensing in support of site remediation. In general, we find that UXO sensing is limited not by raw sensor performance but by phenomenological aspects of the UXO problem, such as soil transmission at radar wavelengths and the presence of background clutter.

**Thus, we recommend that UXO research concentrate on phenomenological investigations that specifically address the unique characteristics of UXO sensing.**

There are a few specific critical phenomenology issues, which are common to all sensing stages, that we recommend be investigated. They include

- UXO target signatures as functions of waveband or sensing technique for a broad range of environmental and operating conditions,

- characterization of vegetation and other naturally occuring and man-made clutter for conditions representative of UXO contamination,

- effects of weather, time of day, and foliation on sensor performance,

- statistics of UXO distribution, both tranversely for density and cluster characterization, and vertically for depth of penetration into the soil.

Finally, the magnitude of the UXO problem indicates that an enormous amount of data must be collected and processed. This is not just a data storage requirement, but rather a requirement on the way data are acquired, assembled, integrated, retrieved, and utilized. Unlike many short-duration military missions, data from UXO surveys must be accessible during short-term cleanup operations, as well as for long-term record-keeping and land-use decision making.

**We recommend that a sophisticated data-handling system be developed and implemented as early as possible. This system should be managed not simply as a "library" but as an important operational asset in guiding sensor development and clean-up efforts.**

The data-handling system should have

– a large data base from historical records, multiple sensor inputs, and detailed mapping of surveyed lands and overlaying of sensor data,

– sophisticated retrieval and sorting by data-base content such as terrain features, soil type, munition type, operational characteristics, etc.

– a skilled staff to interpret the data in support of both ongoing clean-up efforts and technology development.

The data repository should be developed as both an archival resource, and as a research tool for developing, for example, sophisticated data retrieval and visualization techniques. Such a resource would be invaluable in directing future cleanup operations; applications will doubtless also exist for other scenarios, such as rendering lands safe following a military conflict.

## 2.2 PROGRAMMATIC AND SOCIO-POLITICAL CONCERNS

The four-stage structure described above addresses technology development. This development cannot, however, proceed independently of the programmatic and socio-political constraints of the larger problem of transferring former DoD lands to the public. For example, one programmatic concern is the rapid timeline for many of the mandated transfers; technology-development efforts whose utility can not be rapidly demonstrated will probably not be supportable. An example of a socio-political concern that must be addressed is that of system efficacy. That is, what do we mean when we declare lands free of ordnance and how do we deal with the occasional missed UXO? These concerns and others form the basis for several recommendations for action that should proceed in parallel with the technology-development strategy defined in the previous section.

<u>Specific Recommendations</u>

• Demonstration/Validation

In order to ensure that the technologies that are developed according to our four-stage structure can actually be of assistance in clean-up efforts, one must define the appropriate demonstration and validation tests early on. These tests must be designed to verify the predicted performance of the sensor systems, to identify any design shortcomings, and to capitalize on the individual and coupled-sensor strengths.

• Integration

UXO clean-up efforts will proceed with or without any new technologies. If our strategy is to have any merit, it must begin immediately and we must plan how to integrate new technologies rapidly into ongoing clean-up activities. For example, new technologies can be tested and validated at sites where 'traditional' clean-up is occuring as well as at staged UXO sites. In addition, early consideration should be given to how new sensors will be certified so that they can be integrated into clean-up efforts with mimimal legal liability concerns.

• Education

One of the most difficult problems that the DoD faces is public concern over the safety of the citizenry that will have access to transferred lands. We believe that the DoD should have a proactive role in defining future land use and that one way to accomplish this is to establish relationships, early on, with federal, state, and local users of these lands. We recommend that the DoD engage in an aggressive education and public-awareness campaign regarding the hazards of residual UXOs so that it can, in partnership with non-DoD groups, help to direct the sensible use of cleaned-up lands. The penalty for ignoring or even delaying the initiation of these activities is evident, for example, in recent conflicts over the EPA's proposed Military Munitions Rule or the proposed transfer of an unremediated portion of Fort Ord to Monterey County in California. [1,2]

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# 3. BACKGROUND ON UXO CONTAMINATION IN THE UNITED STATES

## 3.1 INTRODUCTION

The UXO contamination problem is unlike any other challenge that the DoD faces. In the broadest military sense, the DoD is charged with protecting the welfare of the citizens of the United States. To do so, it develops both offensive and defensive systems with some assumptions, which change with the times, about the nature of the threat to the United States and the identity of her enemies. Until now, the cost of providing this security has not included the environmental damage that results from development and testing of these systems, nor has it included the cost of guaranteeing civilian safety on contaminated, hazardous lands.

That has all changed. In addition to its ongoing military mission, the DoD is now held accountable for decades of land contamination resulting from weapons testing, training exercises, and munitions disposal, among other things. The federal government has directed the DoD to turn over much of these potentially-contaminated lands to other federal and state agencies and some fraction will even be transferred to the public sector. For the most part, the DoD is responsible for cleaning up the sites before such transfers can be made. Unfortunately, since the amount of land in question is enormous and no one knows exactly where the UXO are, it is difficult to even estimate the time or cost required to conduct the clean-up efforts.

Detection of UXO is critically important to the eventual clean-up effort. There are, however, several factors that affect the design of UXO-detection systems that differ from typical military applications. UXO detection is not simply mine detection 'in disguise'. Many aspects of the UXO problem are favorable for the deployment of sensor technologies. For example, most of the potentially-contaminated sites are under DoD control, therefore there is no need for covertness or long-range communication systems. Second, the systems can be operated at whatever time of day or season or weather conditions are optimum for the technology.

On the negative side, accepted performance criteria or failure rates for military systems will not be adequate for this problem. For example, military systems have certain risks associated with their use or failure; often these risks can be correlated to an estimated number of additional casualties. These are risks that the military planner must weigh when making tactical decisions. UXO contamination must be treated differently as it is unlikely that the public will accept the risk of fatalities in exchange for access to former military lands. Even the treatment of DoD lands contaminated by other hazards, such as fuels or solvents, cannot be compared to the UXO problem. As an example, some soil and groundwater clean-up efforts are driven by analyses that calculate the number of extra deaths as a function of residual contamination level for various cancer types. These numbers are usually very small (e.g., a few per one-hundred thousand) and the public (generally) accepts this level of risk. However, it is safe to argue that, even if the statistical probability of occurence is extremely low, any civilian deaths due to exploding ordnance will be considered unacceptable.

In order to develop a strategy for developing UXO-sensing systems, we must first answer a few questions. They are

- "What is the magnitude of the UXO problem"?
- "How do we currently address this problem"?, and
- "How can we improve upon our current approach"?

In the following subsections we shall discuss the first two questions, while the remainder of the document is essentially devoted to addressing the third.

## 3.2 THE MAGNITUDE OF THE UXO PROBLEM IN THE U.S.

In the simplest sense, the problem is that large amounts of land are potentially contaminated with vast quantities and types of ordnance, some of which may pose a substantial human health hazard (see Figure 3.1). In order to assist in quantifying the magnitude of the UXO problem, we must estimate

- the amount of land to be surveyed,
- the time required to conduct the surveys, and
- the characteristics and distribution of the ordnance.

### 3.2.1 How much land must be surveyed?

According to one estimate [3], there are over 11,000,000 acres of land potentially contaminated with UXO (not including Air Force sites). Approximately 6,000,000 of those acres are on active DoD land, 5,000,000 acres are on Department of Interior land, and less than 100,000 acres are on land slated for Base Realignment and Closure (BRAC). Even if we assume that the active DoD land does not require immediate attention, there are still several million acres of potentially-contaminated land to be surveyed. Furthermore, the land consists of a full range of terrains, vegetation content, soil types, geophysical characteristics, and even includes about 50 underwater sites.

*Figure 3.1* *Cartoon illustration of ordnance-contaminated area; the depiction is intended to show ordnance variety, terrain variability, and examples of clutter. The inset shows the geographic distribution of a small set of ordnance-contaminated locations; red dots refer to Formerly-Used Defense Sites [1] and black dots refer to Major Range and Test Facilities [2].*



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### 3.2.2 How much time is available to conduct the surveys?

Many of the active DoD sites are not slated for any near-term transfer to other federal agencies or the non-federal sector, thus the urgency for clean-up is not as severe as for those whose transfer is imminent. Similarly, many of the potentially-contaminated federal lands are not in use or planned for use by the public sector. Thus, although the DoD ultimately is responsible for clean-up of those lands (under existing legislation), the timeline is not urgent. For sites identified under the recent Base Realignment and Closure rounds, however, the situation is more critical. For sites slated for full closure, the DoD must, by law, initiate closure within two years after a Presidential decision is made and must complete the process within six years. [4] As of January, 1995, 51% of the 70 major closing actions of the 1988, 1991, and 1993 rounds had been completed; bases selected in the 1995 (33 closures, 26 major realignments) round must be closed by 2001.

### 3.2.3 What are we looking for?

The DoD defines unexploded ordnance as "explosive ordnance which has been primed, fused [sic], armed, or otherwise prepared for action, and which has been fired, dropped, launched, projected, or placed in such a manner as to constitute a hazard to operations, installations, personnel, or materiel, and remains unexploded either by malfunction or design or for any other cause". [5]

Unexploded ordnance in the United States results primarily from live-fire testing and training exercises; they can range from small munitions to large (few thousand pound) bombs. For the most part, there will be a subset of ordnance type that are characteristic of each site under evaluation. For example, large bombs dropped from aircraft are not likely to be found on small-munitions live-fire ranges. Similarly, the depth distribution of ordnance can range from on the surface to buried to depths of up to several tens of feet. The actual depth depends on many factors, including the ordnance type and age, method of delivery, angle of impact, type of soil and terrain, and weather conditions at time of ordnance deployment. Table 3.1 displays an example of ordnance distribution with depth resulting from data gathered during range surveys and from site inspections and discussions with personnel involved in explosive ordnance disposal (EOD). [6] The table displays percentages for representative contamination depths; it is intended to be illustrative rather than definitive. Although there are instances where large ordnance have been found at depths of up to 60 feet, most ordnance will be found within a few feet of the surface.

Table 3.1
Representative summary of impacted ordnance distribution with depth.
(Reference 6)

| DEPTH | PERCENT OF TOTAL |
|---|---|
| Surface | 50% |
| to 1-1/2 ft. | 30% |
| to 3 ft. | 15% |
| to 6 ft. | 3% |
| to 25 ft. | < 2% |
| over 25 ft. | < 1% |

We note that, by definition, the only ordnance that represent a hazard are those that are still potentially explosive, thus it is instructive to understand what fraction of total ordnance remains unexploded. These numbers will vary according to ordnance type and age, method of deployment, and geophysical characteristics of the deployment site. Dud rates for older ordnance are difficult to quantify, but empirical evidence indicates approximately 10% of all ordnance may still maintain the potential for explosion. Recent data gathered during clean-up following the Desert Storm conflict indicates that many small munitions, such as dual purpose grenades, had a dud rate less than 5% but that some air-deployed munitions, especially the MK-20 Rockeye cluster bomb, had dud rates in excess of 30%. [7] The high dud rate was attributed to the soft sand and is considered exceptionally high. Even if the dud rate for all ordnance falls somewhere between 5% and 30%, there is still a substantial benefit in the clean-up effort in being able to distinguish explosive from harmless ordnance. Although this may not always be possible, it should be considered as a design goal.

To summarize our attempts at defining the magnitude of the UXO problem, imagine that we had to survey all 11 million acres of potentially contaminated land within, for example, a six-year period. Suppose that such surveys operated 5 days/week, 50 weeks per year; we would then conclude that we had to survey over 7000 acres per day. Furthermore, based on the expected ordnance distributions, we conclude that we would have to survey at least down to a depth of 3 feet to ensure locating most of the ordnance and to greater depths if the intended land use required complete clearance.

Of course, as we mentioned earlier, all 11 million acres will not need to be surveyed and the first task in addressing the problem is to define a prioritization scheme that identifies a much smaller subset of land requiring surveying. Note, however, that even if we reduce by an order of magnitude the requirements on land to be surveyed, we still require coverage of hundreds of acres per day, assuming a highly ambitious schedule of daily surveying over several years. For comparison, typical survey rates for existing ground-based ordnance-location activities are around a few acres per day.

## 3.3 HOW WE CURRENTLY ADDRESS THE PROBLEM

Currently, when an area is suspected of unexploded-ordnance contamination, teams of highly-trained personnel are dispatched to conduct surveys using, typically, hand-held magnetometers, metal detectors, or ground-penetrating radars. In general, these techniques offer high probability of detection with a corresponding high false-alarm rate due to both naturally occurring and man-made ferrous or metallic objects.

As an example, we describe a survey that was conducted in support of remediation of a Nebraska Superfund Site, the Cornhusker Army Ammunition Depot, to detect buried UXO. [8] First, the area was cleared of all surface debris and the site boundaries were marked with grid lines approximately 10 feet wide. Each lane was carefully traversed with the MK-26 Ordnance Detector (dual fluxgate magnetometer hand-held unit) and the operator hand-excavated any shallow subsurface contacts. Any contacts buried greater than 2 feet were marked; suspect areas were subsequently carefully excavated and the ordnance removed or detonated in place. UXO specialists must also operate in the less-controlled civilian communities where occasional UXO are discovered. For example, in 1993 workers excavating in a suburb of Washington, D.C. were surprised to find both conventional and chemical weapons that dated from World War I. [9] Explosive Ordnance Disposal (EOD) specialists were called in to remove the suspect ordnance; by the time clean-up efforts were completed, they had recovered 44 chemical munitions, 97 explosive rounds, and several tons of scrap metal. Finally, a similar incident was reported on Martha's Vineyard in Massachusetts, when beachgoers began finding old munitions on one of the island's popular recreational beaches. [10] Approximately 40 acres were cordoned off and extensive surveys and excavation were conducted throughout 1988 and 1989; entire sand dunes were removed, replaced, and reseeded. For small amounts of land that offers easy access to the surveyors, this methodology of dividing a region into grid lanes, surveying with hand-held instruments, and excavating or detonating, is reasonable. For the total amount of land in the United States that may have to be surveyed for UXO, this approach is both too slow and too costly.

In recent years, much research has been conducted on systems that offer higher coverage rates, such as vehicle-mounted or airborne magnetometers, electro-optic sensors, ground-penetrating radar, and microwave radiometry. Similarly, some effort is underway to enhance the performance of systems by using advanced data-processing techniques. Additionally, sensors have been developed that seek to distinguish explosive from inert ordnance by sensing the presence of explosives *in situ.* An excellent summary of relevant UXO-sensing technologies is provided in reference [1]. Unfortunately, despite the vast resources expended on this problem, no single sensor has emerged that is capable of meeting the diverse requirements for a UXO-sensing system. As a result, many researchers and users are focusing on combinations of sensors that may offer complementary capabilities. Often, however, there is little systematic attempt to define, *a priori*, an optimum combination of sensors that is both widely applicable and whose features offer the greatest degree of orthogonality.

In a more general sense, common laments among those charged with addressing the UXO clean-up problem are that research efforts in UXO sensing are not well coordinated, are not based on a good understanding of users' needs, and have not evolved from a general strategy designed to address the UXO problem in the United States. Very often, UXO-sensing programs are follow-ons to existing work in countermine efforts that support combat operations. This is sensible in that there are many similiarities in detecting mines and UXO, but deployment and clearance requirements are often vastly different. A countermine system that must operate covertly and rapidly but only has to detect over a roadway, for example, will look very different from a system designed for UXO sensing that may have minimal time constraints but that may have to operate over large tracts of land and detect ordnance buried several feet deep.

## 3.4 HOW WE PROPOSE TO IMPROVE UPON THE CURRENT APPROACH

As mentioned in a recent Government Accounting Office report, "no formal mechanism or strategic plan exists to ensure that a fully coordinated U.S. research and development effort is leveraged at the [UXO detection] problem". [11] One of the purposes of the study that we have undertaken for SERDP is to assist in designing such a strategy. In brief, we propose a systematic approach to addressing the disparity between the capabilities of existing UXO-sensing technologies and the requirements dictated by the clean-up of suspect DoD lands. Our strategy lies in defining a multi-tiered approach to UXO detection that has the following features:

- Each tier successively reduces the amount of land to be surveyed,
- UXO sensing will rely on combinations of sensors that provide complementary capabilities and advanced-data-processing techniques whose goal is high probability of detection with low false-alarm rates,
- Focus will be on existing, proven technologies, with assessments made of the improvements necessary to achieve the design goals for UXO sensing.

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# 4. SELECTION HIERARCHY FOR ADDRESSING UXO-SENSING PROBLEM

## 4.1 A FOUR-STAGE STRUCTURE

We recommend a multi-tiered approach to provide a systematic methodology for addressing the UXO-sensing problem. The primary function of the hierarchy we propose is to reduce the total amount of land to be surveyed to levels that can be accomodated in a reasonable time frame, while simultaneously providing high probabilities of detection and low false-alarm rates. The stages of the hierarchy are displayed in Figure 4.1, with a brief description of the function of each. We describe four stages: a prescreen stage and three subesequent sensing stages. Each of these stages will be described in greater detail in subsequent sections but an overview is offered here.

The intention of the prescreen stage is to prioritize those lands that require surveying – either because of intended land use or known contamination information – by the degree of urgency that their clean-up mandates. A second goal is to identify those suspect lands that are not likely to contain ordnance or whose intended land use does not require immediate attention. Thus, by focusing on both the history and destiny of a site, one hopes to reduce, by a considerable degree, the amount of land that must be addressed for surveying in the near term.

For those lands identified in the prescreen stage as requiring surveying, we suggest a cuing stage that offers rapid coverage, and whose goal is the identification of UXO fields. This sensing stage, which is most likely to require an airborne platform, will not target the detection of individual UXO, but rather, the clusters and concentrations of UXO representative of testing and training exercises.

Some lands identified during the prescreen stage may bypass the cuing stage altogether, either because of specific information regarding the location of UXO or because of inaccessibility of the terrain to the cuing platform. These lands, together with those identified during the cuing stage as potentially containing UXO fields, would be subject to the next stage of sensing, which we call detection. The goal in this stage is to detect and map locations of individual UXO within the boundaries identified in either the prescreen or cuing stages. The platform for this stage of sensing would most likely be ground or near-ground based, and the UXO maps would provide the neccessary information for assessment of the future use of the land or for initiation of the clean-up efforts.

As a final sensing stage, we propose a classification stage whose goal is to distinguish those ordnance that pose a hazard to human safety or the environment from those that are unlikely

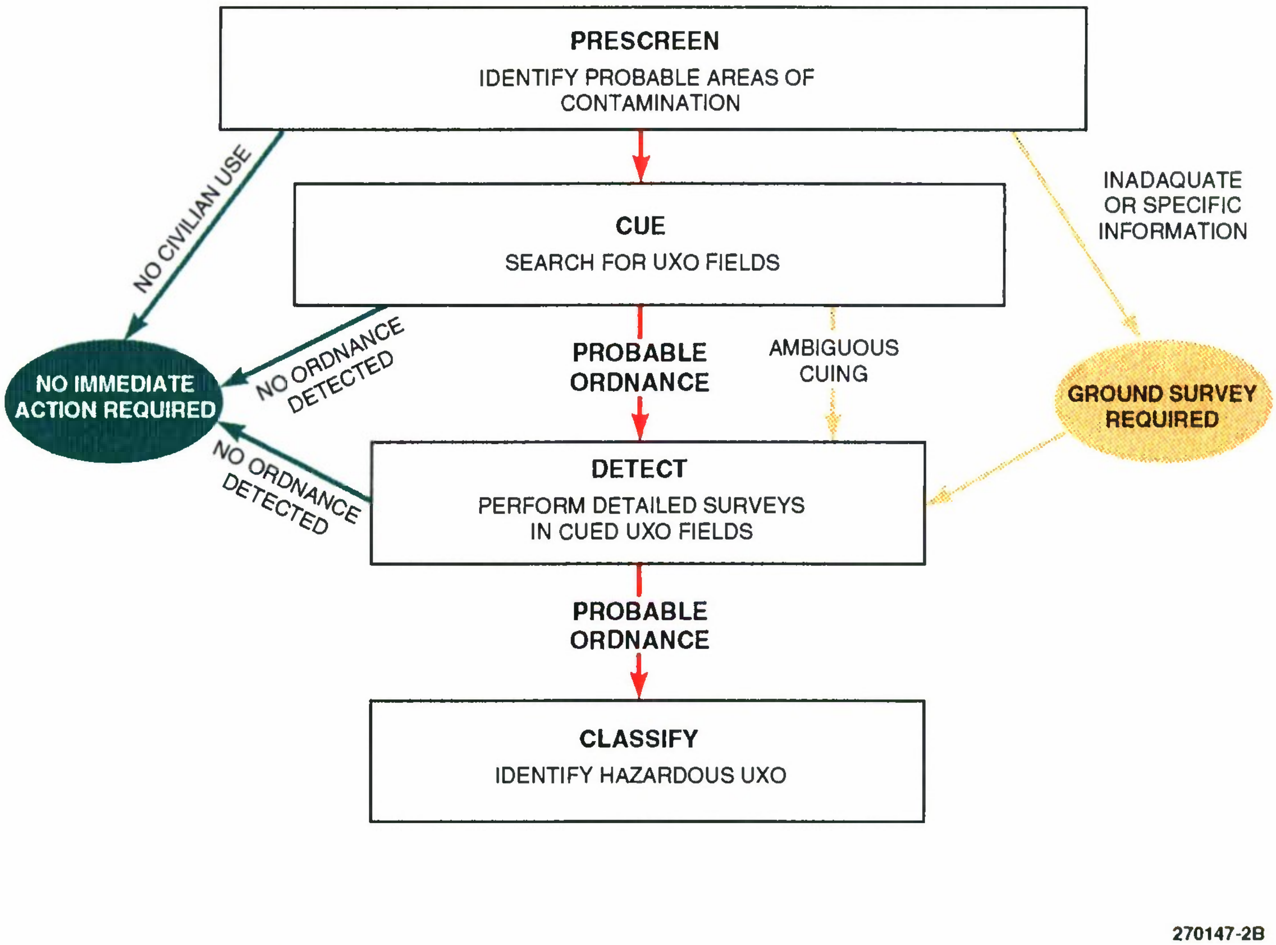


*Figure 4.1* *Proposed four-stage selection hierarchy for UXO sensing.*

to explode, which we call nuisance ordnance. One possible implementation of this stage is to interrogate individual ordnance that have been located in the detection stage and provide a secondary map layer that identifies only those that are hazardous. Alternatively, the classification sensors could be integrated onto the detection platform and provide that information concurrently. The motivation for this classification stage is the relatively large payoff that results if all ordnance do not have to be treated as hazardous. If one accepts the nominal 10% dud rate as a guideline, then knowing which ordnance are hazardous offers substantially improved ability to define land use and can facilitate clean-up efforts for those lands whose use is already determined.

In Figure 4.2, we display a notional chart of the four stages described above, where the parameter that we seek to minimize is the total amount of land requiring surveying. Our design goal is that the four stages of the selection hierarchy reduce the amount of land to be surveyed by orders of magnitude; thus the ordinate — the amount of land to be surveyed — is plotted on a log scale. We refer to the chart as notional because we have not conducted a detailed systems analysis that would allow us to assign real numbers to the ordinate axis. We believe that such an analysis can and should be conducted a priori, especially as one completes the prescreen stage. In other words, if a large reduction in land requiring immediate surveying can be achieved in the prescreen stage, then those lands can be assessed for the applicability of the cuing stage. Much of this assessment will depend on the types of land and ordnance that survive the prescreen process. For example, if most of the identified lands are heavily forested and suspected of large (i.e., deep) ordnance, the cuing platform may not offer enough applicability to warrant its development. If, however, a substantial amount of identified lands is in desert-like environments, or has seasonal cycles of defoliation, or has significant surface UXO, then the cuing stage may be worth developing because of the large reduction in survey time that it can offer. Similarly, by identifying individual UXO, the detection stage seeks to reduce the total amount of land to be considered for clean-up to just those areas actually containing ordnance. Depending on the ordnance density, this stage can offer substantial payoff. Finally, as we discussed earlier, the classification stage offers a potential for an order of magnitude reduction in ordnance count that will require specialized treatment or clean-up.

In the following sections, we will outline our recommendations for implementation of the four stages described above. We treat the prescreen stage somewhat differently from the sensing stages, focusing mainly on what resources can be accessed to provide the necessary information at this stage. The implementation of each sensing stage — cuing, detection, and classification — requires evaluation of numerous factors. These factors include

- the selection of appropriate sensor technologies,
- concerns related to the sensor fusion and data processing, and
- information required to assess payoff and risks associated with each sensing stage.

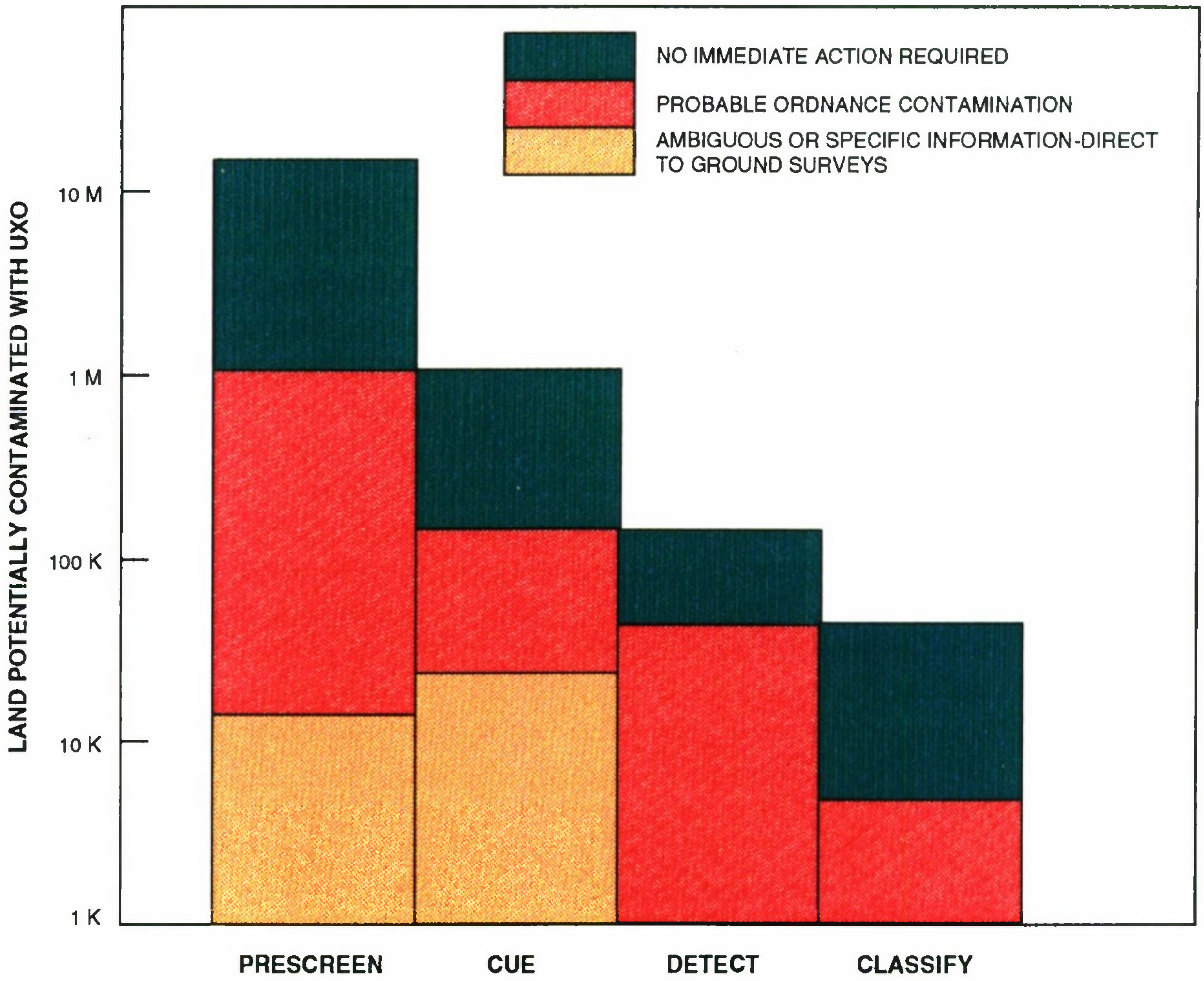


*Figure 4.2* *Notional chart of the proposed four-stage selection hierarchy depicting the relative reduction in survey requirements at each stage.*

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### 4.1.1 Sensor Technologies

Most of the remainder of this document will discuss sensor technologies. Our recommendation of sensor technologies to be deployed during each stage results from reviews of the status of relevant systems and our assessment of the capabilities of existing or almost-existing technologies. We have used, as the basis for our recommendations, summaries such as the JPL report on UXO-sensing technologies [1], extensive literature surveys of technologies that can be related to UXO sensing, and the results of our own research in mine and buried and obscured-object detection. In each section in which we discuss sensor technologies, we will focus on:

- what combination of sensors can provide the complementary information that is required to achieve high probabilities of detection and low false-alarm rates,
- what are the bases for our recommendations,
- what basic phenomenology issues must be addressed in utilizing those sensors, and
- who are some of the key players and what are the important programs in sensor development and measurements.

As with any large-scale, multi-faceted problem, there are surely going to be circumstances where our sensor selection or methodology is inappropriate. We have tried to define the most generally applicable systems, but the reader is reminded that certain scenarios, such as continuously-foliated or underwater sites, may not be covered by any of our recommendations. In these cases, it is best to adopt the four-stage structure that we define, but to focus on site- or application-specific sensor technologies.

### 4.1.2 Sensor and Data Fusion

In the second category, we will address issues relevant to the fusion of sensors and the treatment of the resultant data. The term data fusion is used to refer to a wide variety of techniques for extracting and correlating information from different sources. The application of data fusion techniques for sensing UXO provides a scientific method for the systems-level integration of multiple sensors.

There are two sensor-fusion concerns that almost all sensor combinations have in common. They are registration and sensor complementarity. The sensors that we propose will acquire their imagery at different resolutions, from different platforms, and even at different times. To successfully implement a data-fusion algorithm, these different data sets must be registered and combined in a common coordinate system. The issue of complementarity refers to the choice of sensor combinations. One must ensure that there is both overlap in the functionality of each sensor type, as well as orthogonality, so that the sensors do not just offer the same data by a different mechanism. For example, if one sensor can detect all metallic objects with a high-probability of detection and another sensor can detect all metallic objects as well as all naturally-occuring clutter, then the combination can be used to definitively identify metallic objects and reject clutter. Thus, the objective of seeking sensors with a high degree of complementarity is to maximize the probability of detection and minimize the false-alarm rate.

Data fusion is usually accomplished in one of two ways: distributed or centralized. Distributed systems are characterized by each sensor performing detection or feature extraction and then passing the information into a data correlator. Centralized systems collect all of the information from the sensors and fuse the sensor-level data before detection. Each of these systems has merit. Typically, the distributed system is chosen because of the reduced data-processing requirements. In contrast, centralized systems offer the advantage of fusing at the image level. In order to decide which fusion technique is most appropriate, both the sensor and target phenomenology must be well understood. Since the UXO problem covers a large variety of target types and environmental conditions, it is likely that the best fusion algorithms will be adaptive.

For each sensing stage, we will discuss the fusion issues that are unique to the sensor combinations within that stage. We will also briefly discuss the data-processing issues that must be addressed, but we assume that the exact fusion-algorithm architectures will require more detailed analyses of the related phenomenology.

### 4.1.3 Payoff and Risk Assessment

Finally, for each sensing stage, we will discuss the information required to develop accurate payoff and risk models. That is, we will not conduct a detailed risk assessment associated with each stage (that is outside the scope of this study), but we will attempt to define what knowledge is required to conduct such an assessment. Because the format will be similar for each sensing stage, we provide an overview of our model development in Appendix A.

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# 5. PRESCREEN STAGE

The first stage in the selection hierarchy provides perhaps the largest reduction in area to be surveyed. The intention of the prescreen stage is to examine, for example, the 11 million acres of suspect land and make informed decisions that reduce that quantity by an order of magnitude or more. In general, land examined during the prescreen phase can be grouped into three categories. In the first category would be all those lands that are either in civilian use or intended for civilian use. These lands would be automatically targeted for subsequent surveying. The second category would include all those lands where there is specific information regarding location of UXO, for example, a known munitions-burial site or some other unambiguous indicator of UXO. Likewise, these lands would also automatically be targeted for surveying. In the third category would be all remaining lands that would have to be reviewed for both their potential to contain ordnance and their intended land use. It may be possible, for example, to find land that has a high probability of contamination but that has no immediate intended use; in this case, it would receive a low priority for surveying. The ultimate result of the prescreening phase is to identify those lands with probable ordnance contamination that require immediate or near-term attention. In order to make this assessment, there are several sources of information that can be exploited.

First, a thorough review of the known or suspected ordnance activities should be conducted to define probable regions of ordnance contamination. (In fact, this is done now as part of the site evaluations). These data should come from sources such as site archives, historical records, utility-company surveys, interviews with attending personnel, and satellite and aerial imagery, to name a few. Tables 5.1 and 5.2 show examples of some of the past and current imagery available over the United States from both satellites and airplanes. We do not propose that these images will locate individual ordnance, but rather may help to locate areas of activity, to document terrain or coastline changes, and to provide, in some cases, "before and after" images of suspect lands.

A second parameter that is relevant in narrowing down the scope of the survey effort is the type and deployment method of ordnance used at each site. For example, often both the transverse and depth extent of the UXO distribution can be estimated from knowledge of the munition size, angle of fire, method of delivery, and weather during activity. For sites with recent ordnance activity, it is still possible to develop models for ordnance fate that can input soil characteristics, terrain features, weather information, for example, and predict the distribution of ordnance with some success. These models should, of course, be validated experimentally. Other sources of information include the results of past UXO clearance activities, either from clean-up of former military sites [1] or past military conflicts such as the 1973 Arab-Israeli War, Afghanistan, or

**Table 5.1**
Examples of past and current satellite imagery available over much of the United States

| SATELLITE | COVERAGE DATES | RESOLUTION |
|---|---|---|
| LANDSAT | 1972 - Present | 30 m - 120 m |
| AVHRR | 1978 - Present | ~ 1 x 4 km |
| SPOT | 1986 - Present | 10 m - 20 m |
| IASIS | 1991 (?) - Present | 2 m - 10 m |
| EROS | 1995 - Future | 2 m |

**Table 5.2**
Examples of airborne imagery available from various agencies over conterminous United Sates

**ARCHIVED VISIBLE IMAGERY DATA SETS AVAILABLE FROM:**

| | |
|---|---|
| — Bureau of Indian Affairs | Dates Range From |
| — Bureau of Land Management | 1939 - 1990 |
| — Bureau of Reclamation | |
| — Environmental Protection Agency | |
| — National Park Service | Coverage Irregular but |
| — Department of Agriculture | Includes Continental U.S., |
| — U.S. Air Force | Alaska, Hawaii |
| — U.S. Army | |
| — U.S. Navy | |

**NATIONAL AERIAL PHOTOGRAPHY PROGRAM (USGS)**

— Acquires cloud-free aerial photography every 5 to 10 years of 48 conterminous states.
— Includes leaf on/leaf off cycles
— Dates range from 1980 - Present

**SIDE-LOOKING AIRBORNE RADAR PROGRAM (USGS)**

— Radar images of most of U.S. available with 10 -15 m resolution
— Dates range from 1980 - Present

Desert Storm. [2] These activities offer valuable information about UXO distribution in real and varied terrains and can often provide critical information such as the relative fraction of surface to subsurface UXO as a function of soil and ordnance type.

Once the prescreening data are gathered and suspect lands prioritized on the basis of their probable contamination and intended land use, we must decide what we do with those lands that we conclude do not require immediate attention, either because they are deemed uncontaminated or because we foresee no immediate use for them. The prescreening stage (or indeed, any stage of our proposed process) has the potential for declaring lands clean that actually contain ordnance. This is one reason why we suggest prioritizing lands for near-term attention; this still implies that suspect lands may someday be surveyed but that we order our surveying so that lands with the lowest-probability of contamination (or least likelihood of transfer out of the DoD) will be at the bottom of the list.

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# 6. CUING STAGE

## 6.1 SYSTEM OVERVIEW

Once a subset of land has been identified that can be surveyed in the cuing stage, we must design an optimum-sensor suite for carrying out those surveys. Since we assume that the amount of land to be covered is still large (but smaller than 11,000,000 acres), we suggest an airborne platform that offers high areal coverage. Note, for the purpose of offering specific recommendations for this study, we cannot suggest a single system that will meet the needs of all possible terrains under all possible conditions. Thus, we have chosen to focus on land-based ordnance contamination, and we will attempt to identify the terrain and ordnance conditions that are most appropriate for the sensing system we suggest. For underwater contamination, or deeply-buried ordnance, one must choose a different sensing scheme, but one can still follow the methodology that we outline in this document. It is our intention to propose a system that offers the greatest flexibility and capability based on the majority of scenarios of ordnance contamination in the United States.

The cuing system that we propose has the following features:

— one or more airborne platforms with onboard differential GPS and INS for accurate navigation and positioning,

— a dual-band (X-band and UHF) synthetic aperture radar (SAR) sensor to detect surface and shallow-buried ordnance,

— an electro-optic sensing system that passively detects at least two infrared bands to measure emissivity changes associated with thermal anomalies resulting from surface or shallow-buried ordnance, that provides visible co-registered imagery to assist in clutter rejection, and contains one active visible to near-infrared channel to distinguish between man-made and naturally occuring surface ordnance or ordnance-like objects,

— sensor-fusion techniques that take advantage of each sensor's unique contributions to the overall system,

— data processing that focuses on identifying clusters or concentrations of "ordnance," so that ordnance fields, rather than individual ordnance, are identified.

In Figure 6.1, we show a cartoon of a likely implementation of the sensor combination that

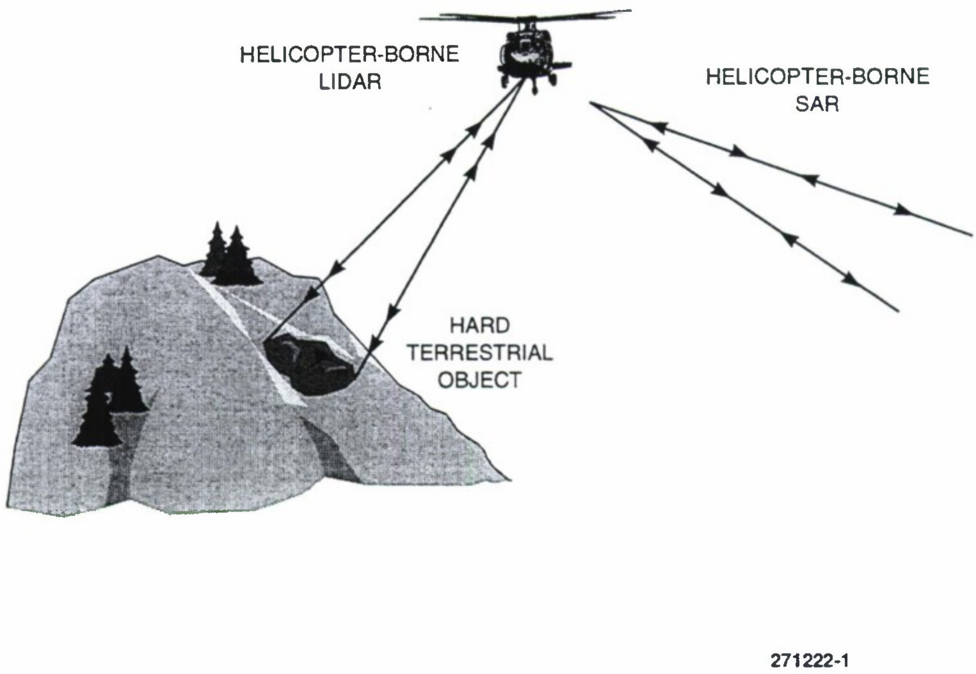



*Figure 6.1* *Cartoon depiction of airborne SAR and EO system deployment for UXO-cuing.*

we describe above. Note that, although we suggest deploying the two sensor types from the same platform, we do not believe that the SAR sensors can fly concurrently with the same field-of-view as the electro-optic sensors. Note also that the system design is intended to detect only surface and shallow-buried ordnance, with some foliage obscuration acceptable. Thus, as mentioned before, sites that are suspected of containing only deeply-buried ordnance with little surface component are not candidates for the cuing stage. In the vast majority of instances, however, surface ordnance will co-exist with buried ordnance.

### 6.1.1 Synthetic Aperture Radar Sensor

#### 6.1.1.1 Introduction

The task of locating UXOs has generally been carried out using ground-based sensors [1], such as magnetometers, gradiometers, and ground-contact radars. Although ground-based sensors can be fairly effective in detecting both surface and buried UXOs, they lack wide-area coverage capability. Because the number of acres of potentially-contaminated land is large, the wide-area coverage offered by airborne sensors is necessary in the cuing stage. In addition to wide-area coverage capability, airborne UXO-cuing sensors should have resolution high enough so that the minimum target-to-clutter (T/C) ratio can support a high Pd/Pfa (probability of detection/probability of false alarm) ratio. One airborne sensor with the potential to satisfy the cuing platform requirements is a sub-meter resolution Synthetic Aperture Radar (SAR).

In the past, both positive and negative results using airborne SARs for UXO detection have been reported. [1,2] Some of the negative results may have been caused by inadequate signal processing or inadequate understanding of phenomenologies. SARs are imaging radars used in two configurations – either down-looking or side-looking. In either configuration, a monostatic radar is mounted on an airplane, and as the airplane travels, radar signals are transmitted and radar echoes are recorded. The recorded radar echoes are then coherently integrated to form synthetic apertures for imaging. Down-looking SARs can have high resolution along the direction of flight but relatively poor cross-track resolution; they have narrow swath widths. Down-looking SARs are not suitable for wide-area UXO cuing. Side-looking SARs can have both high range (perpendicular to flight path) and cross-range (parallel to flight path) resolution. The range resolution of a side-looking SAR is determined by its bandwidth; the cross-range resolution is determined by the size of the synthetic aperture and the operating frequency. The size of a synthetic aperture is determined by the integration angle; the width depends on the elevation angle (Figure 6.2): a small elevation angle corresponds to a large swath width. A typical SAR swath width is more than 1 km; a typical airplane speed used to form synthetic apertures is 180 to 360 km/hour. Therefore, a typical SAR can achieve coverage rates of a few hundred square kilometers per hour, which should be satisfactory for the UXO-cuing application.

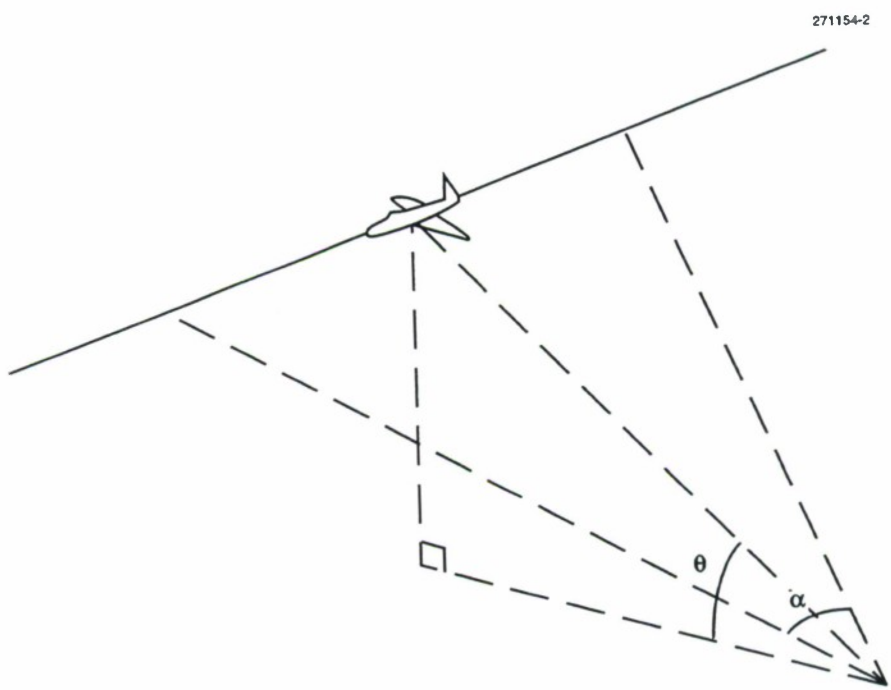



*Figure 6.2* *A SAR configuration, α is the integration angle, θ is the elevation angle.*

In order to discuss the use of SARs for UXO detection, one must estimate the strength of the radar return, which is defined, in part, by the radar cross section (RCS). The RCS of a UXO target (T) is a function of UXO geometry, environmental parameters (such as soil properties and terrain), and radar parameters (such as frequency, aspect angle, polarization, and resolution). The choice of optimum radar parameters is dictated by the specific UXO phenomenology under investigation, but some generalizations are possible. For example, as long as the size of the resolution cell (pixel) is larger than or comparable to the size of the UXO, the pixel RCS is dominated by the target return. The signal return from clutter (C), on the other hand, is generally proportional to the size of the resolution cell. Thus, resolution cells smaller than the target offer no advantage and just increase the amount of data to be processed; resolution cells much larger than the target can be dominated by clutter. In general, a SAR resolution comparable to the size of the UXOs will offer maximum T/C ratio. The physical dimensions of UXOs are generally small, about 1 meter to 10 centimeters. Therefore, a sub-meter resolution SAR should be used. Current high-resolution SAR technologies offer a foot or better resolution in both the range and cross-range dimensions, and they should be adequate for UXO cuing applications.

There are two types of high-resolution SARs that we recommend be utilized in the cuing stage: low-frequency (for example, UHF) and high frequency (X-band or higher). We will briefly describe the significant features of these two bands, why we believe that they are effective, and what issues must be addressed before they can deployed as cuing-stage sensors.

Low-frequency ultra-wideband SAR

SARs operating at L band (1000 - 2000 MHz) or lower frequencies use ultra wideband technologies to achieve sub-meter resolution. The low-frequency radar energies can penetrate vegetation very well; for example, an average of only 5 dB two-way losses in dense foliage have been measured with a UHF-band SAR. [3] Under certain soil conditions, the low-frequency radar energies can also penetrate soil relatively well. For example, sub-meter soil penetration depth can be expected in U.S. western-desert environments, which typically have moderately lossy (20dB/m average soil attentuation). [4] The low-frequency ultra-wideband SARs may therefore be useful for detecting both unobscured and obscured UXOs, whether the obscuration is from foliage or shallow soil coverage.

Examples of airborne deployments of a low-frequency SAR are provided by the ground-penetrating (GPEN) radar experiments that were carried out using a VHF/UHF SAR at Yuma AZ, in June, 1993. [5] The target deployments included metallic anti-tank mines (M-20), plastic anti-tank mines (M-80), and anti-personnel mines (Valmara); these mines were deployed in a 200 by 200 square meter area of relatively-low clutter. One-meter resolution imagery was processed for this area. The M-20 mines were metallic disks approximately 1 foot in diameter and 5 inches high.

The M-80 mines were 1 foot square and 4 inches high. The dielectric constant of the M-80 mines is roughly 2 to 3, which is similar to the dielectric constant of the desert soil; thus, detection of the mines was not expected. The Valmara mine is about the size of a soda can; thus, it was not expected that the VHF/UHF SAR would have high enough resolution to detect these targets.

The average clutter RCS per pixel for the entire GPEN site and for the minefield area were -23 dB and -28 dB, respectively (Figure 6.3). The SAR imagery of the minefield revealed that more than 10 dB T/C was achieved for both the surface and shallow-buried M-20 mines; Figure 6.4 shows the SAR image of the minefield. As expected, the M-80 and Valmara mines were not visible in the SAR image. An Automatic Target Recognition (ATR) algorithm for minefield detection was developed and tested on an image of the GPEN site. [6] This ATR algorithm detected many of the surface and buried M-20 mines and detected the buried and surface minefields, with 3 false minefield cues in a 4-square-kilometer area of SAR imagery. We also examined the dependence of elevation angle on target-to-clutter ratio. Figure 6.5 shows the measured RCS of both the M-20 mines and the clutter as a function of elevation angle for HH polarization. [2] We see from these measurements that T/C decreases as the elevation angle decreases; in addition, the swath width decreases as the elevation angle increases. Thus, the optimum range of elevation angles, where more than 10 dB T/C ratio is achievable with reasonable swath widths, is about 30 to 50 degrees.

High-frequency SAR

SARs operating at X-band (8 - 12 GHz) or higher frequencies routinely offer better than one foot resolution. They have been successfully applied to detecting unobscured targets and to imaging terrain features and surface vegetation. The high-frequency radar energies do not, however, penetrate soil or vegetation well enough to detect buried or foliage-obscured targets. Thus, high-frequency SARs are useful for directly detecting unobscured UXOs. Additionally, the high-resolution imagery of terrain features and surface vegetation that they provide can be used to assist in surface-clutter rejection.

An experiment to detect surface UXOs on a desert terrain was carried out using a Ka band (33 GHz) SAR with 1 foot resolution. [7] The UXO targets included rocket bodies, rocket fins, rocket pieces, shells of different sizes, and submunitions. The average clutter RCS per unit area was -12 dB at about 12 degree elevation angle (Figure 6.3). Using advanced data-processing techniques such as a Polarimetric Whitening Filter (PWF) [8] and multilook image-speckle-reduction algorithms, almost all UXOs were detected with a minimum of 4.5 dB T/C ratio. [7] The detection threshold was set at a level that produced a probability of false alarm of 0.001. Analysis of the data indicated that the optimum elevation angle was about 10 degrees, which is smaller than the optimum elevation angle for the low-frequency SAR system previously described.

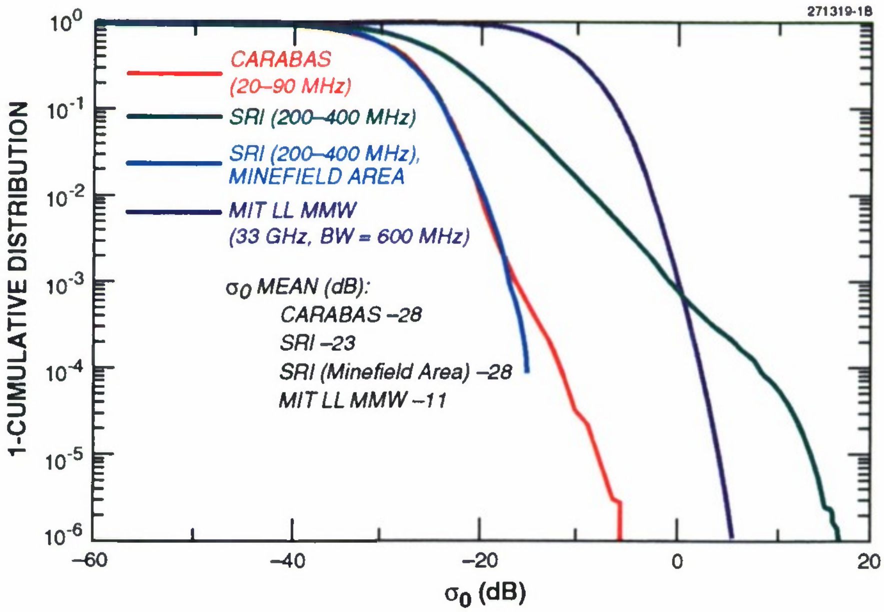
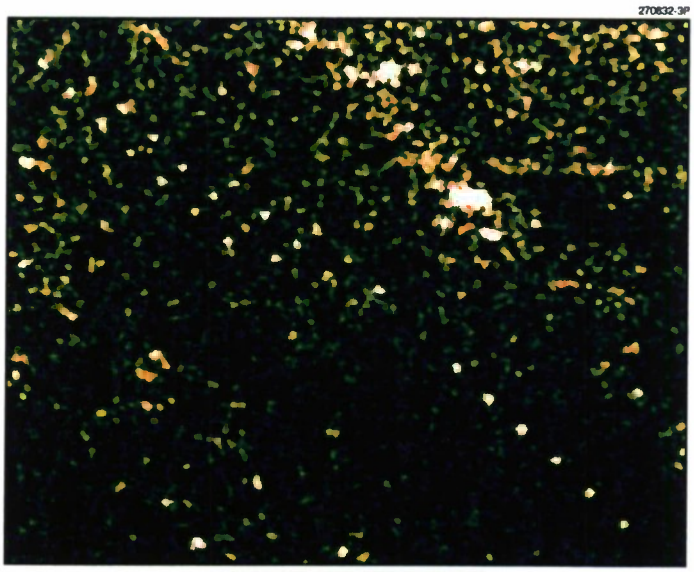



*Figure 6.3* *Desert clutter statistics in the VHF/UHF and Ka bands.*




1993 YUMA GPR EXPERIMENT
MINES, 1 m × 1 m RESOLUTION
SRI SENSOR, LL IMAGE

*Figure 6.4* *A UHF SAR image of M-20 mine field.*

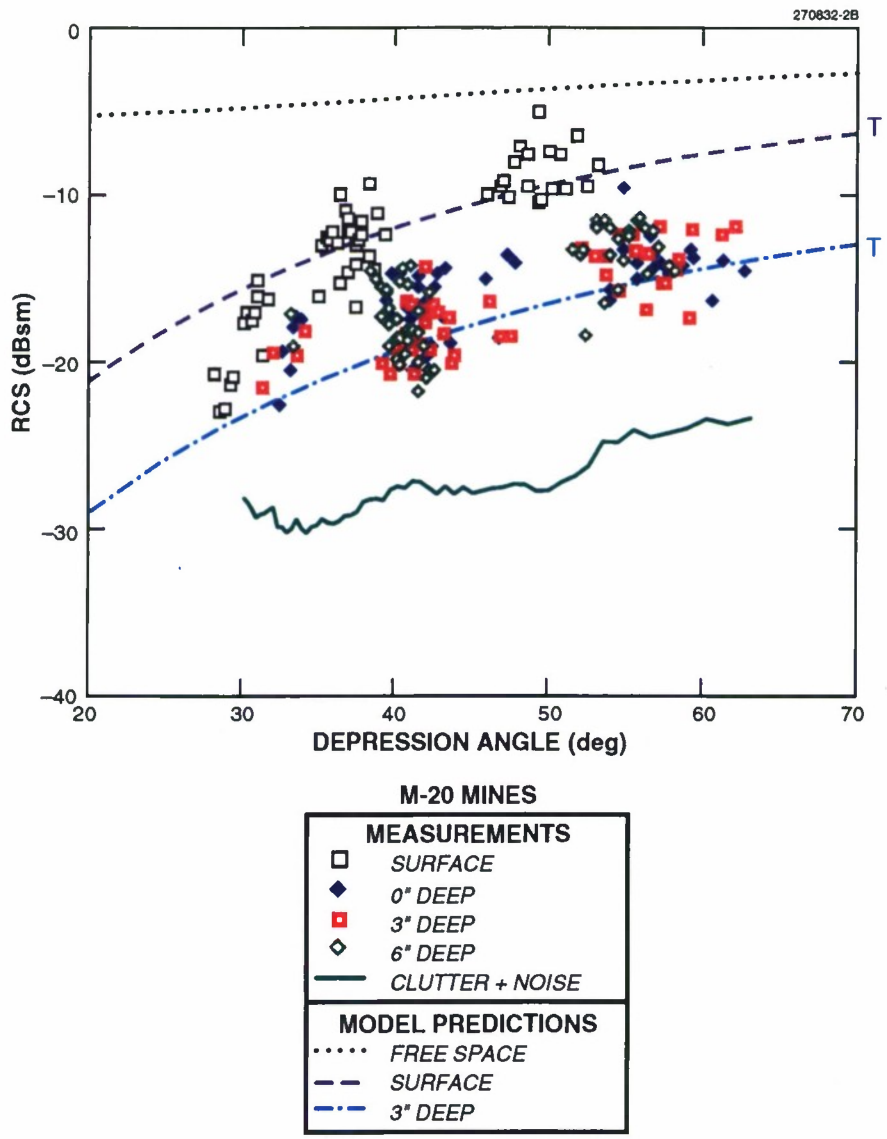



*Figure 6.5* *RCS of M-20 mines as a function of elevation angle for the HH-polarized, 200-400 MHz SRI FOPEN II SAR system.*

Table 6.1 [7] summarizes the UXO detection results for different polarizations (HH and fully polarimetric) and for both one and five looks; SAR's utility in detecting surface UXOs is clearly demonstrated. Most of the moderate to large targets were detected; the smaller (1.5 inches in diameter and 2 inches in height) M-75 and M-42 submunitions were not. The rocket body designations R1 through R6 refer to different orientations with respect to the SAR sensor; both full polarization and multiple looks conferred an advantage in being able to detect these targets.

Table 6.1
A UXO detection summary using a Ka-band SAR with 1 ft resolution. Check marks denote detections.

Radar Aspect Angle = 90·
Threshold Set for PFA = 0.001

| | One Look | | Five Looks | |
|---|---|---|---|---|
| Polarization | HH | PWF | HH | PWF |
| Threshold (dBsm/m$^2$) | .12 | -3.9 | -5.6 | -7.9 |
| Threshold (dBsm) | -8.68 | -12.7 | -14.4 | -16.7 |
| Clutter Stand.Dev. (dB) | 5.8 | 3.2 | 2.5 | 1.6 |
| Debris Trail | √ | √ | √ | √ |
| Bomb Fin | √ | √ | √ | √ |
| 50 Cal Shell Casings | (not detected) | √ | √ | √ |
| 20/30 mm Shell Casings | √ | √ | √ | √ |
| 40 mm Shell Casings | √ | √ | √ | √ |
| Rocket Pieces | √ | √ | √ | √ |
| Rockets | R1,R2,R6 | R1,R2,R5,R6 | R1,R2,R6 | R1,R2,R4,R5,R6 |
| Submunition, M-75 | 0 of 5 | 0 of 5 | 2 of 5 | 2 of 5 |
| Submunition, M-42 | 1 of 5 | 0 of 5 | 1 of 5 | 1 of 5 |

#### 6.1.1.2 Recommendations for SAR UXO Cuing System

The results of the 1993 Yuma GPEN experiment suggest that high-resolution, low-frequency SARs can be used to detect both surface and shallow-buried UXOs. Similarly, the results of the UXO-detection experiment using the Ka-band SAR indicate that high-frequency SARs can be used to detect surface UXOs and can provide valuable input for surface clutter rejection. In addition, Sandia Laboratory's Ku-band SAR also has demonstrated encouraging results for surface UXO detection, although the system resolution and results are classified. For any sites that include surface or shallow buried UXOs, we recommend that high-resolution (low frequency and high-frequency) SARs should be included in the UXO cuing platform. We have focused on results of MIT Lincoln Laboratory experimental efforts to support this recommendation largely because of the limited number of experimental efforts that have been reported in the open literature that have been specifically designed to examine surface and shallow-buried UXOs with airborne SAR systems. These limited experiments are, however, by no means the sole verification of the potential SAR-systems' utility; many other research efforts have employed airborne SARs for mine and buried-object detection and a substantial number of theoretical analyses have been conducted that support our claims [9-13].

Our specific recommendation is that the UXO cuing system consist of two sub-meter resolution SAR systems: one operating at L-band or lower frequency, possibly UHF band, the other operating at X-band or higher frequency, possibly X or Ka band. These SAR systems should be side-looking and fully polarimetric.

The sub-meter resolution is required in order to achieve high T/C ratios. The side-looking feature is required for wide-area coverage. The fully polarimetric feature is required in order to support sophisticated signal-processing algorithms, such as the PWF, for background-clutter reduction. The low-frequency SAR may operate at a high-elevation angle, such as 30 degrees, and the high-frequency SAR may operate at a low-elevation angle, such as 10 degrees.

The purpose of recommending a dual-band cuing system is to support data-fusion algorithms for false alarm reduction and surface clutter rejection. The minefield detection exercises in the 1993 Yuma GPEN experiment [5] and the surface UXO detection using a Ka band SAR [7] were carried out for relatively low-clutter desert environments. Searching for low RCS UXOs in a high-surface-clutter environment requires a significant surface-clutter rejection, and the ability to perform data fusion for surface-clutter rejection becomes crucial.

#### 6.1.1.3 Issues to be Addressed in the Design of the Cuing-Stage SARs

A successful UXO cuing system needs to optimize system parameters, such as frequency bands and elevation angles and should utilize appropriate signal-processing and data-fusion algorithms. Determining the optimum system parameters and algorithms requires understanding of both phenomenological and system-related issues.

We recommend that studies and experiments should be conducted to investigate the following phenomenological and signal-processing issues:

1. RCSs or SAR signatures of UXOs. Although some effort has been allocated to collecting RCSs or SAR signatures of UXOs, the large variety of targets requires that more experimental investigations be undertaken.

2. Clutter statistics corresponding to typical UXO-contaminated areas. In recent years, many data-collection activities using the UHF, L, X, and Ka band sensors have accumulated data on clutter. Some of the collected clutter data may be similar to that found at UXO-contaminated sites. Thus, we suggest that existing data be reviewed for its applicabiilty and new data be acquired where necessary.

3. Soil electrical properties corresponding to typical UXO-contaminated areas. The RCSs of UXOs are strongly dependent on multipath loss and attenuation, which are functions of soil electrical properties. We recommend that site-specific studies of soil electrical properties be conducted to assist in estimating the RCS of representative targets.

4. Radio-frequency interference (RFI) corresponding to the frequency band and deployment locations. At some locations, RFI can be significant in the UHF band. Since UXOs are usually low-RCS targets, effective RFI-rejection algorithms are required to enhance UXO visibility. Several RFI-rejection algorithms have been developed [14,15], and it is likely that these algorithms can be adapted for use in new scenarios.

5. UXO cluster statistics. The primary function of the cuing stage is to identify areas associated with UXO fields, rather than to pinpoint the location of individual UXOs. We make the assumption that, in most cases, there will be clusters or high-density areas of positive returns that can help delineate UXO fields. This assumption should be verified, either by records from past remediation efforts or from ongoing testing exercises.

6. ATR algorithms for UXO detection. Manual detection is not practical for wide-area cuing, thus algorithms must be developed that automatically provide target detections, clutter rejection, and delineation of target clusters corresponding to UXO fields. Although similar ATR algorithm development has been undertaken for other programs, such as ARPA's Critical Mobile Target program and foliage-penetration (FOPEN) program, the unique

phenomenology of the UXO problem warrants dedicated development efforts. In addition to applying existing algorithms to UXO detection, we recommend that new innovative signal-processing approaches be explored. For example, technology improvements, such as ultra-wideband and wide-angle SAR imaging, will offer better and more detailed measurements of target signatures. Large gains in surface and buried-UXO detectability may be achieved by incorporating target signatures and propagation effects directly into signal-processing algorithms.

In addition to the investigations recommended above, there are several systems issues that require attention. For the most part, the issues that we identify below are being explored by existing programs, although not necessarily for the application of UXO sensing. We suggest that the progress of these efforts be followed and, where possible, their results adapted to SAR-based UXO sensing.

1. Time associated with SAR image formation. Processing SAR imagery can be very time and resource consuming. Most SAR image processing has been done off-line, which could represent a bottleneck in the wide-area UXO cuing system. A few efforts have been directed at real-time processing; for example, AFWL and ARPA are involved in the Radar Detection of Concealed Targets (RADCON) program to develop a real or near-real-time processor for image formation and detection of obscured targets. This effort should be completed within two or three years. The technology for the processor to support real-time cuing may also be available from the unmanned air vehicle development efforts as well as the ARPA RASSP program [16].

2. Motion compensation for SAR image formation. Motion compensation is crucial in high-resolution SAR image production. Some motion-compensation technologies have been developed and tested for a narrow-integrating-angle, high-frequency SAR, but, motion-compensation for wide-integrating-angle, low-frequency SARs is more challenging and is, at present, typically done off-board post mission. Efforts such as ARPA's FOPEN program and the DIA/CMO-sponsored GPEN SAR program (executed by ARL) are addressing this problem.

3. Image registration methodology for the two-band SAR images. Image registration is a difficult task, yet crucial for data fusion. The fact that the low-frequency SAR and the high-frequency SAR may operate at different elevation angles makes the image registration problem more difficult. There are a number of existing government programs working on multi-sensor or multiple-image registration, for example, ARPA's Semi-Automatic Image Processing (SAIP) ACTD program is developing algorithms for multiple-pass SAR image registration..

#### 6.1.1.4 Existing SAR systems

Over the years, there have been several developments in SAR technologies and system developments in the United States. Some of these technologies and systems may be reconfigured or combined to form an entire or a part of the UXO cuing system. The following lists some of the relevant airborne SAR systems and their respective performances.

1. The MIT/LL MMW SAR. It operates in a Ka band frequency; it is fully polarimetric with 1 foot resolution. [17]

2. Sandia's VHF/UHF/Ku/Ka band SARs. It operates in several frequency bands, from upper VHF to UHF and to Ka and Ku bands; it is horizontally polarized with resolution better than 1 foot. [18,19]

3. ERIM's Data Collection System. It operates in a X band frequency; it is fully polarimetric with 1 foot resolution. [20]

4. The NASA/JPL SAR. It operates in UHF, L, and C band frequencies. It is fully polarimetric with 4 to 10 meter resolution. [21]

5. The SRI FOPEN II. It is a VHF/UHF ultra wideband impulse radar; it has three VHF/UHF frequency bands (100-300, and 200-400, and 300-500 Mhz); it is horizontally polarized with 1 meter resolution. [22]

6. The SRI FOPEN III. It is a VHF/UHF ultra wideband impulse radar; it is fully polarimetric with 1 meter resolution.

7. The NAVY/ERIM P-3 SAR. It contains a fully polarimetric UHF radar operating from 200-900 MHz with 1ft x 2 ft resolution and can also operate at X, C, and L bands. [23]

The SAR sensor technologies that we recommend for the cuing stage are currently available, although not, to our knowledge, generally integrated into one system. Sandia's Ku/UHF band SAR can operate at each band independently but not simultaneously; it may prove useful as more verification data becomes available. One could, however, combine existing systems such as the Sandia Ku-band SAR and the NAVY/ERIM P-3 system, or ERIM's Data Collection System and the SRI FOPEN III, for example, to develop a SAR UXO-cuing system. Examples of the several Government programs addressing SAR-sensor development for obscured and surface-object detection include ARPA's FOPEN, AFWL's RADCON, ARL's FOPEN, and ARL/DIA GPEN systems.

### 6.1.2 Electro-Optic Sensor Suite

We recommend that electro-optical (EO) sensors be part of the suite of UXO cuing sensors. This section provides a brief overview of electro-optical sensing techniques as applied to the UXO cuing task; we discuss the key concerns related to UXO detection by EO sensors and describe a potential EO cuing system. More detailed explanations of the fundamentals of electro-optical sensing and its application to UXO detection can be found in, for example, References 24-26.

The EO sensor in UXO cuing must provide

- direct detection of individual surface UXOs,
- indirect evidence of buried UXOs, and
- corroborating evidence for false-alarm reduction, when used in concert with other sensors, specifically, the SAR system described in the previous subsection.

The cuing portion of the UXO architecture requires that these functions be performed at a high area-coverage rate and with a high probability of detection of UXO fields. The cuing-sensor suite need not detect each UXO, but it must be able to detect a sufficient number so that a UXO field can be identified for subsequent, more detailed interrogation.

The detection process depends on the target and background phenomenology and on statistics of the clutter environment. The discrimination features that are available for classification algorithms are functions of the sensor, its mode of operation, and the targets. This section of the report provides some insight into the first three listed functions. Concerns related to fusing EO-sensor data with that of the SAR system are discussed in section 6.2.

#### 6.1.2.1 Overview of EO Sensing

Electro-optical sensing for the cuing portion of the UXO problem utilizes electromagnetic radiation spanning 0.3 through 25.0 μm. At both ends of the wavelength regimes the atmosphere becomes less transparent to the electromagnetic radiation to the point that useful data in the atmosphere cannot be collected. The exact boundary of the useful range for EO sensing is specific to the problem and sensor design chosen. It is beyond the scope of this report to provide a complete tutorial on EO sensing, but a brief overview of some of the sensor aspects is useful. Specifically, the following items are addressed

1. target phenomenology associated with sensor-spectral regimes,
2. radiometric imaging versus spectrometry, and
3. passive versus active-sensing techniques.

The target phenomenology exploited by the EO sensor depends both on the spectral coverage of the sensor and the means by which the target signal is generated. Passive sensors rely either on self-emission (in the infrared wavelength regime) or reflected ambient radiation (in the visible and near infrared regime). Active sensors provide their own illumination source. Table 6.2 lists the spectral regimes, their designations, and abbreviations used throughout this section.

Table 6.2 [1]
Spectral Band Definitions

| Designation | Abbreviation | Wavelength Coverage (micron) |
|---|---|---|
| Visible | Vis | 0.3 to 0.76 |
| Near Infrared | NIR | 0.76 to 1.0 |
| Short Wave Infrared | SWIR | 1.0 to 3.0 |
| Middle Wave Infrared | MWIR | 3.0 to 7.0 |
| Long Wave (Thermal) Infrared | LWIR | 7.0 to 15.0 |
| Very Long Wave Infrared | VLWIR | 15.0 to 25.0 |

Target Phenomenology

The phenomenological concerns associated with passive sensors depend on the sensor-wavelength range. All bodies radiate electro-magnetic radiation based on their equilibrium temperature (the so-called blackbody radiation). As the temperature of a body increases more radiation is emitted and the peak of the specific intensity curve shifts toward shorter wavelengths. Figure 6.6 is a notional curve indicating the increase in total energy with temperature and the shift of the location of the peak with temperature. [27] The Planck blackbody function is plotted for temperatures ranging from 200° to 400° K. Notice that the total energy (area under the curve) decreases with decreasing temperature, whereas the peak of the curve increases with decreasing temperature. The wavelength at the peak of the curve ($\lambda\mu m$) is a simple function of the blackbody temperature:

$$\lambda\mu m = 2880 / T$$

The peak of the curve is at 10 μm for a 288° K body. A sensor intended to detect objects in the 250° to 450° K range requires sensitivity in the LWIR regime, although some signal is also available in the MWIR region.

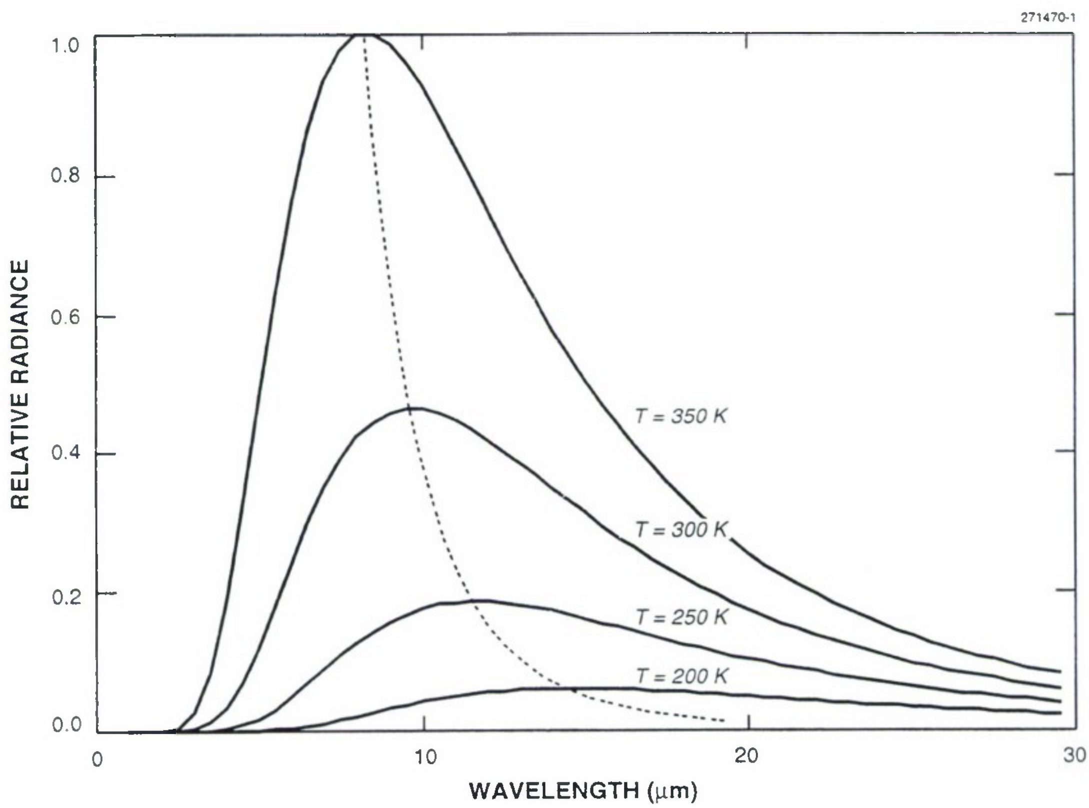



*Figure 6.6* *Typical blackbody radiation curves.*

One element of the UXO problem is the detection of buried objects in addition to surface objects. One cannot utilize any sensor that relies on reflected radiation (either passive or active) for buried-object detection. Buried objects are detected by the perturbations of the surface temperature they induce and several experimental systems have been developed that detect these perturbations. [28-31] A body with a high thermal mass below the surface will minimize diurnal fluctuations of the surface temperature. Figure 6.7 is a notional chart that indicates the diurnal variation of the radiant temperature for some typical materials. [24] The sharp change in the apparent temperature at the diurnal transition points (sunrise and sunset) of natural materials with respect to high-thermal-mass objects forms the basis for buried-object detection. [32] A broadband LWIR radiometer can detect differences in surface radiant temperature. Large thermal-mass buried objects will reduce the temperature variations at the surface at the transition periods, thereby increasing the likelihood of detection. The expected signature from the buried object is a function of the thermal mass of the object and the local thermophysical properties of the soil.

At shorter wavelengths, one must rely on reflection of the ambient radiation for the EO signal. In the visible, NIR, SWIR, and to some degree the MWIR, the EO signal is dominated by reflection. The primary passive source is the sun. Passive EO sensing relying on reflected solar radiation limits operation to daylight hours, but this limitation is unlikely to be significant for UXO detection. An alternative passive source, which would primarily be useful in the SWIR regime, is atmospheric emissions due to airglow. The actual signal formed by an object reflecting solar (or airglow) radiation is a strong function of the surface optical properties of the object.

## Radiometric Imaging and Spectrometry

Measuring the radiant temperature of a scene is an example of a radiometric measurement of an object. It typically utilizes sensors with a broad wavelength coverage. An alternative, passive EO technique is to collect image data within multiple, narrow spectral regimes. In this case, the features for classifying detected objects are directly related to the spectral variations of surface emissivity or reflectivity of the object. For gray objects, that is, objects whose surface optical properties do not vary with wavelength, radiometric techniques are viable. For non-gray materials, however, the spectral variations of the surface-optical properties can be used to distinguish between objects. The structure within the spectral signature of the material may provide features with which to distinguish between UXO and natural materials. An example of such a phenomena is the presence of the 'red edge' in vegetation; this is the wavelength (around .69 $\mu$m) where the spectral reflectivity is reduced relative to wavelengths on either side of this 'edge'. The cause of this reflectivity dip is the transition from chlorophyll absorption, which dominates in the visible, to scattering in the near-infrared, which is dominated by the surface structure of leaves.

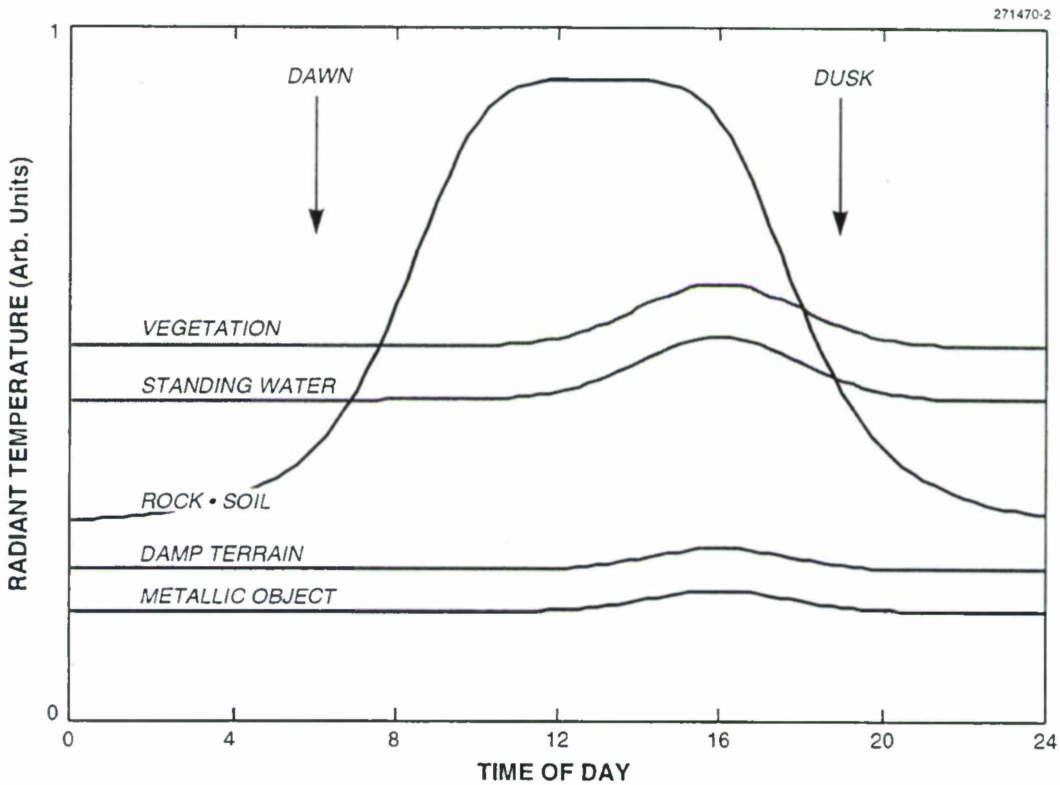



*Figure 6.7* *Notional view of the diurnal effect on radiant temperature for typical materials.*

## Active Sensing

Another valuable technique to distinguish UXOs from vegetation or other naturally occuring clutter is to actively illuminate the scene. Active EO sensing typically utilizes a laser as the illumination source. Active systems have the advantage of being able to operate at any time of day. In addition, by proper selection of the wavelength it may be possible to take advantage of special phenomenology. For example, chlorophyll in plants can be made to fluoresce at 0.685 $\mu$m when illuminated with radiation in the visible spectral region. This feature could be exploited to assist in the rejection of false alarms due to vegetation.

Systems have been developed that exploit another EO feature: polarization. [33,34] Metallic objects preferentially reflect radiation in a plane normal to their surface. The ratio of the return signal in the parallel and perpendicular polarization components is determined by the surface optical properties of the target. Table 6.3 is a list of the degree of polarization and total reflectance for selected materials characterized in support of the STAMIDS ATTD (refer to Appendix C for further details). In general, natural objects show a low degree of polarization; whereas man-made, metallic objects exhibit a high degree of polarization. The separation of the man-made from natural objects in this chart is indicative of a potential classification feature.

Table 6.3
Polarization Percentage and Reflectance for Selected Materials [33]

| Item | Reflectance (%) | Degree of Polarization (%) |
|---|---|---|
| Green Plant | 31 | 9 |
| Cow Dung | 41 | 12 |
| Dead Grass | 30 | 18 |
| Rock | 33 | 19 |
| Squirrel Hole Soil | 16 | 22 |
| Watered Soil | 31 | 21 |
| Disturbed Soil | 21 | 23 |
| Scraped Soil | 31 | 21 |
| GEMSS Soil Background Scraped | 30 | 21 |
| M75 GEMSS | 39 | 20 |
| Bar Mine Background Plowed | 32 | 20 |
| Bar Mine, PGMDM | 30 | 5 |
| M-19 | 32 | 64 |
| M-15 | 21 | 74 |
| PT-MI-BA-III, Czech | 20 | 75 |
| PM60 | 25 | 81 |
| TM62 | 85 | 90 |

A brief summary of the advantages and disadvantages of EO sensing applied to the UXO cuing-stage requirements is given in Table 6.4. The primary advantage of EO sensing is the ability to cover a large area with a high probability of detection. The primary limitation is that this high probability of detection is achieved only for surface and near-surface objects. It should also be noted that EO UXO cuing cannot take place during a period when the potential UXO fields are snow covered. This should not be a serious constraint for the UXO cuing problem since the time of day and time of year can be selected to optimize performance.

Table 6.4
Advantages and Disadvantages of Selected Electro-optical Components

| Component | Advantages | Disadvantages |
|---|---|---|
| Passive EO Radiometers | Large area coverage, proven technology<br><br>Low risk, system exists<br><br>Amenable to ATR and Sensor fusion techniques | Direct detection of surface objects only, limited time of day operations (daytime or transition period)<br><br>Requires target-phenomenology data base |
| Spectrometers/Hyperspectral Imagers | Ideal for phenomenological investigations, large data volume with respect to radiometric imager | Inherent low SNR.<br><br>Requires large target-phenomenology data base |
| Laser Illuminators | Moderate risk, systems exist, independent of time of day, may offer best rejection of natural clutter | Potential added complexity and cost.<br>Requires large target-phenomenology data base |

### 6.1.2.2 Recommendations for EO UXO Cuing System

Numerous experiments to detect surface and shallow-buried objects using MWIR and LWIR sensors have been conducted and at least one system has been fielded that uses laser-based active sensing of surface objects as well. [34-36] These experimental results, as well as other phenomenology studies, analyses, and modelling, all indicate that EO sensors could play a valuable role in supporting the UXO cuing function. [37-39] We recommend an EO-sensor combination whose primary components are listed in Table 6.5. The performance characteristics listed in this chart are provided for guidance only and should be supported by a rigorous design analysis.

Table 6.5
EO Components of an UXO Cuing System

| Sensor Element | Characteristics |
|---|---|
| Platform | Airborne: Helicopter of fixed wing |
| Passive LWIR Sensor | 8-12 μm, ~ 0.8 mrad resolution, ~ 20° FOV, linear array |
| Passive MWIR (or SWIR) Sensor | 3-5 μm (1-3 μm), 20 mrad resolution, TBD FOV array area |
| Passive Visible Sensor | 0.3-1.0 μm, 0.5 mrad, area array (with spectral filter capability), ~ 20° FOV |
| Active Reflectometer & Polarimeter | 1.0 μm linearly polarized, coaligned with LWIR sensor |
| ATR | Real time fusion of imagery from all EO sensors as well as other sensors on platform |

The sensor suite that we recommend is similar to the Remote Minefield Detection System (REMIDS) described in some detail in Appendix C. [40] The significant differences are the addition of a MWIR channel and algorithm development to support sensor fusion.

#### 6.1.2.3 Required Phenomenology Research

UXO cuing requires the ability to automatically detect individual objects. The UXO cuing function requires automatic detection of UXO fields. In order to build an automated UXO-detection system, one must have characterized both the UXOs and their environment. One must have knowledge of the UXO characteristic signatures in the relevant wavebands. In addition, the signatures must be collected under conditions consistent with the operation of the selected sensor.

It may not be possible to collect target signatures under all conditions that UXO are expected. In this case, one must rely on models and simulations to interpolate (or extrapolate, if necessary) the signatures to the proper regime. The purpose of the phenomenology measurements in this case would be to validate the simulations. Once the simulations are validated, they can then be used to design and evaluate UXO detection architectures.

There is another reason to pursue the collection of both UXO target and clutter data, which is to assist in defining the optimum sensor-system parameters. For passive sensors, the choice of detector, integration-time requirements, and operational configuration all should be optimized based on the expected target and clutter signal levels. Similarly, for active systems, even the choice of laser wavelength and other characteristics may depend on the types of targets being examined as well as the environment in which they are likely to be found.

We recommend that the EO UXO phenomenology-research effort focus on collecting:

1. passive infrared data (LWIR and MWIR) and visible data using the sensors in the proposed wavebands and focal-plane configurations on representative UXO pieces.

2. high-resolution spatial and spectral data on UXO pieces for the purposes of model and simulation validation. Hyperspectral imaging techniques may be useful for this task.

3. reflectance and polarimetric data on representative UXO pieces. This task should be performed under both controlled laboratory conditions and in operational modes.

4. background data, such as vegetation and other naturally-occuring clutter, as well as other man-made clutter, for any radiometric and spectral features that could be exploited.

All of the above measurements should be conducted for a wide range of sensor-operating conditions, e.g., time of day, solar position, sensor altitude and speed, and environmental and meteorological conditions. The purpose is to build a target and clutter data base sufficiently large so that the potential UXO classification features can be verified and evaluated.

In addition, there are many phenomenological and systems issues that are identical or similar to those discussed in the SAR section: the statistics of UXO clusters in helping define a UXO field, concerns related to real-time processing, image registration, and automating the detection scheme, to name a few. There are also a few concerns that are unique to the problem of fusing EO and SAR sensors; these issues will be discussed in Section 6.2.

#### 6.1.2.4 Key Players

The JPL report [1] contains a comprehensive list of the sensor and system vendors in the area. In addition, Table 6.6 lists four groups who have fielded Standoff Mine Detection (SMD) systems that exhibit capability that could be extended to the UXO cuing problem.

Table 6.6
Standoff EO Mine Detection Systems Applicable to UXO Cuing [35]

| System Name | Acronym | Agency |
|---|---|---|
| Remote Minefield Detection System | REMIDS | US Army Waterways Experimental Station |
| Airborne Minefield Detection and Reconnaissance System | AMIDARS | US Army Belvoir Research, Development & Engineering Center |
| CounterMine Airborne Detection and Surveillance | CMADS | Martin Marietta Missile System |
| Airborne Mine Detection & Surveillance | AMDAS | US Marine Corps, Naval Coastal System Center |

In addition to the above organizations, which have direct experience with field operations of a potential EO UXO-cuing system, a number of organizations have on-going data collection programs which could be of interest to the UXO community. A selection of programs operating hyperspectral sensors is listed in Table 6.7.

Table 6.7
Hyperspectral Data Collection Programs [36]

| System Name | Acronym | Agency |
|---|---|---|
| Hyperspectral | HYDICE | |
| Airborne Visual & Imaging Spectrometer | AVIRIS | Jet Propulsion Laboratory |
| Multi-Spectral Infrared Camera | MUSIC | The Technical Cooperative Program, JTP-14 (US, UK, Canada, Australia) |

Table 6.8 lists additional organizations whose work is relevant to the UXO EO cuing problem.

Table 6.8
Organizations with EO UXO Related Experience

| Organization | Applications |
|---|---|
| US Army Night Vision & Electronic Sensor Directorate-Countermine Division, Ft. Belvior, VA [32,37,38] | Airborne Standoff Minefield Detection System (ASTAMIDS), Algorithms, Data Acquisition |
| US Army Research laboratory-Special Sensors Branch [30] | Phenomenology, Sensors |
| US Army Mobility Equipment Research & Development Command, Ft. Belvior, VA [39] | Minefield detection and mitigation |
| Office of Naval Research [41] | Airborne Infrared Measurement System - LWIR imaging for water surface detection |
| US Naval Surface Warfare Center, Coastal Systems Station, Panama City, FL | Sensors, phenomenology, algorithm development |
| US Marine Corps Landing Force Technology Program | Multi-spectral standoff minefield detection |
| Defense Research Establishment, Suffield, Alberta, Canada [28,42,43] | LWIR minefield detection, sensors, data acquisition, algorithms |
| Lawrence Livermore National Laboratory-Airborne Standoff Mine Detection Project, Electro-Optical Mine Detection Program [29,44] | Sensors, data acquisition, algorithms |
| Massachusetts Institute of Technology Lincoln Laboratory-Laser & Sensor Applications & Advanced Systems and Sensors Groups | Sensor, data acquisition, algorithms |
| Los Alamos National Laboratory [45] | Sensors, data acquisition |
| Environmental Research Institute of Michigan-Electro-Opticsl Laboratory, Ann Arbor, MI | Sensors, data acquisition, algorithms |
| Jet Propulsion Laboratory, California Institute of Technology, Center for Space Microelectronics [46] | Hyperspectral imaging with acousto-optical tunable filters |

## 6.2 SENSOR FUSION AND DATA PROCESSING

### 6.2.1 Sensor Fusion

As we discussed in Chapter 4, there are some concerns common to almost all sensor-fusion schemes, such as image registration and sensor complementarity. For the particular problem of fusing SAR and EO data, both these concerns deserve elaboration.

We have proposed, in the SAR system, two frequency bands that operate at different depression angles. The low-frequency SAR operates optimally at 30 to 50 degrees of elevation; the high-frequency SAR operates optimally at about 10 degrees of elevation. To further complicate the situation, the EO system that we recommend would most likely be nadir viewing. Thus, in order to optimize each sensor's performance, we require a single platform that can house both sensor types and can operate in a multiple-look fashion, where one look (the high-frequency SAR) is at significant standoff from the target area, the second look is at moderate standoff (the low-frequency SAR), and the third look is directly over the area under interrogation. (Note that a single platform is not critical to our discussion; the fusion issues are only slightly changed if multiple platforms are deployed.) Fusing data from the two sensor types requires both that the sensor platform fly at a speed and altitude that can accomodate all sensors and that a geometric registration of images from each sensor be performed. The choice of airborne platform will be dictated primarily by the EO sensor, which requires the slowest speed and lowest platform altitude of the two sensor types; we therefore recommend a helicopter. The image registration can be facilitated by the advance placement of survey reflectors or other calibration aids; the reflectors would be used to provide a common ground-plane coordinate system for the image-registration algorithms.

The issue of sensor complementarity must also be examined in greater detail before a specific system design can be implemented. For example, we are postulating that the SAR sensors will permit one to detect surface and shallow-buried or partially-obscured UXOs, but that substantial effort must be expended to reduce the effect of clutter, especially due to vegetation. The EO sensors will permit one to detect even small surface UXOs and perhaps some shallow-buried targets, but will, in addition, offer substantial advantage in reducing the contribution of vegetation clutter. Thus, although there is some overlap in the sensors' functionality, there is also sufficient orthogonality to warrant investing in the combination.

We are aware of at least one effort to investigate the utility of combining SAR sensing with laser radar and passive-IR sensing. Under ARPA's critical mobile target program, MIT LL conducted an investigation whose goal was to improve the detection of stationary ground targets in a background of terrain clutter. Overlapping images of targets in clutter were collected by a millimeter-wave SAR and the MIT LL infrared airborne system, which included a forward-looking $CO_2$ laser radar and an 8 - 12 μm passive IR sensor. [47]

Although the data acquired in this sensor-fusion study and the scope of the study were limited, useful information was obtained on the degree of correlation of radar and IR detections in high-resolution imagery. One of the more useful results showed that the two-sensor-types' detection of clutter was uncorrelated. Data is shown in Figure 6.8 that displays the false-alarm density, after combining IR and SAR detections, as a function of SAR-detection threshold. The data is shown compared to the theoretical results that would have resulted if the two sensor detections were uncorrelated. Assuming that individual sensors would operate with a high-probability of detection, uncorrelated clutter detection has exactly the desired effect – reducing the false-alarm rate without a significant degradation in probability of detection.

### 6.2.2 Data Processing

A final issue to be addressed, whether fusing different sensors or relying on single-sensor returns, is that of automating the detection process. We have discussed the desirability of real-time data processing, which has the main advantage of alerting the operator to unusual or interesting signal returns in a timely fashion. Even if the processing is done post-mission, both the UXO detection and clutter rejection should be automated, owing to the large volume of data that will be acquired on each airborne survey. The architecture of the ATR algorithms can be determined after the phenomenology issues surrounding, for example, cluster statistics and target signatures in the different sensor regimes, have been addressed. We recommend that a survey of possible techniques and methodologies be performed and that field tests be conducted to validate the concepts.

## 6.3 PAYOFF/RISK ASSESSMENT

### 6.3.1 Potential Payoff

The function of the cuing phase is to isolate fields of UXOs and declare other areas as free from contamination. By deploying sensor suites from an airborne platform, this stage has the potential to greatly reduce the amount of land that requires detailed surveying.

### 6.3.2 Applicability

For the cuing phase to be an effective means of searching for UXO fields several conditions must be present:

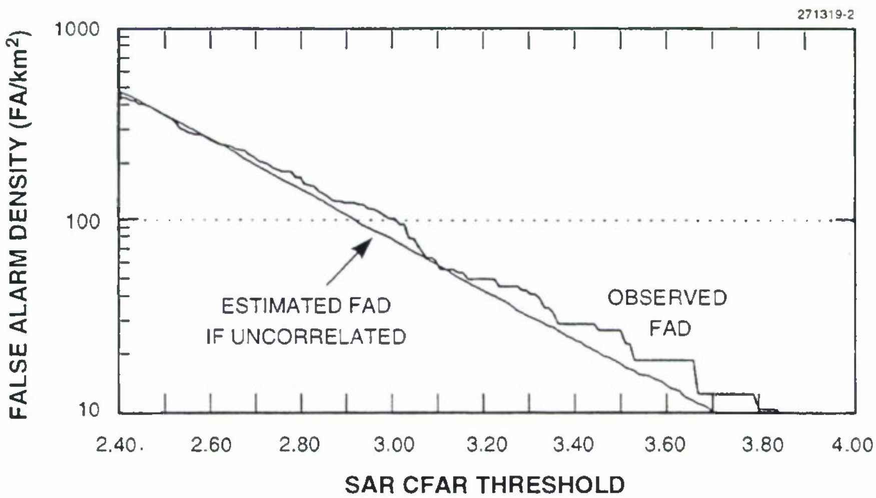



*Figure 6.8* *False alarm density of an IR-SAR system.*

1. UXOs must appear in clusters. If the UXOs are scattered uniformly across the land, then there is little benefit derived from a survey based on detecting fields.

2. There must exist a correlation between surface or near-surface UXOs and buried UXOs. Since the cuing-phase sensors will only be able to detect surface and near-surface UXOs, the detection of buried UXOs requires that surface features be present. Surface features may either be other UXOs or a very distinctive change in the surface-soil properties.

3. The site to be surveyed must be amenable to the types of sensors present in the cuing platform. Heavily foliated sites will not be surveyable using the cuing sensors.

4. The probability of detection of a UXO field must be very high. The probability of detection of this stage drives the entire system probability of detection.

5. The false alarm rate must be low. The false-alarm rate must be sufficiently low so as to eliminate large tracts of land from the contamination list. Otherwise there is little benefit to using the cuing phase.

6. The benefits of developing the fused-sensor system must be sufficient to warrant the added cost and complexity over deployment of the individual sensors.

### 6.3.3 Issues Associated with Risk Assessment

The decision to develop the cuing system is dependent upon the required detection probability and the amount of land that can be surveyed using the cuing phase. The risks inherent in the development of the cuing stage are related to both system costs and public health and safety. Although we cannot provide an actual risk assessment here, we can suggest a few parameters that must be evaluated in order to make this assessment.

Table 6.9 provides a summary of the research required to support the development and evaluation of a cuing-stage sensor suite and a preliminary relative assessment of the costs and benefits for each. The table is shown for illustrative purposes; an actual risk assessment will require that a more formal analysis be conducted.

Table 6.9
Research and Development Investment Risks

| R&D EFFORT | RESEARCH RISK | COST | BENEFITS |
|---|---|---|---|
| SAR Phenomenology | | | |
| Clutter Statistics | Low | Low | Moderate |
| Target Signatures | Low | Low | Moderate |
| Soil Electrical Props. | Low | Low | Moderate |
| RFI Interference | Low | Low | Moderate |
| EO Phenomenology | | | |
| Target and Clutter Statistics | Low | Moderate | Moderate |
| Systems Issues | | | |
| Cluster Statistics | Low | Low | Moderate |
| Real-Time Processing | Moderate | Moderate | Moderate |
| Motion Compensation | Moderate | Moderate | Moderate |
| ATR Algorithms | Moderate | Low | High |
| Sensor fusion | Moderate | Low | High |

In addition to assessing the relative investment risk of the cuing stage, one must also address the impact on public health and safety. These risks are driven by the reality that, even with a high-probability-of-detection system, there will be a certain number of acres that are declared clean, but in fact are not. The number of acres of land mis-identified as clean is approximately equal to

$$\text{Contaminated Acres} = ( 1 - P_d)*N_{acres}$$

where $N_{acres}$ is the number of acres surveyed, and $P_d$ is measured in the probability of detection per acre. Since the cuing system is keyed on fields and not individual munitions, isolated munitions will be missed. Given the enormous amount of land to be surveyed and that it is impossible to build a perfect detection system it is likely there will be thousands of acres mis-identified. The amount of missed fields that can be tolerated is a function of the amount of risk that is willing to be undertaken.

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# 7. DETECTION STAGE

## 7.1 SYSTEM OVERVIEW

Several categories of lands may find themselves subject to the detection stage of UXO sensing. They are those lands identified during the prescreen stage as either not accessible to the cuing platform or about which specific information leads one directly to a detailed survey, those lands identified during the cuing stage as potentially containing UXO fields, and those lands interrogated during the cuing stage that resulted in ambiguous or questionable survey results. The detection stage is applied to those lands described above and functions to detect and map locations of individual ordnance. This stage will not, presumably, operate over the large land area required of the cuing stage, but may nevertheless be required to survey tens of thousands of acres. One requirement for detection that was not expected of the cuing-stage sensor system is the ability to interrogate to several feet below the ground surface. To meet these requirements, we propose a system with the following features:

— a ground or near-ground based platform with integrated differential GPS for motion compensation and position marking of suspect ordnance to within 50 cm position accuracy,

— magnetic (gradiometric) or induction sensors for surface and buried ferrous or nonferrous-metallic-ordnance detection,

— a ground-penetrating radar sensor for detection of ordnance, rocks, voids, and other clutter,

— sensor and data fusion algorithms to assist in exploiting the complementarity between the two sensor types.

Figure 7.1 displays a possible depiction of a detection-sensor platform. Since both the sensitivity and resolution of the aforementioned sensor types fall off rapidly with range, we recommend either a helicopter-deployed towed sensor suite, as shown, or a vehicle-mounted sensor suite utilizing a boom. The exact choice of platform will depend on the terrain and probable distribution and types of ordnance to be located; we suggest that the detection-sensing package be designed for deployment on both platforms. Some standoff of the sensor suite from the area under interrogation is desirable to minimize the hazard to the sensor operators and instrumentation. Ground-contact sensors can be considered only if remotely operated vehicles are deployed as the delivery mechanism.

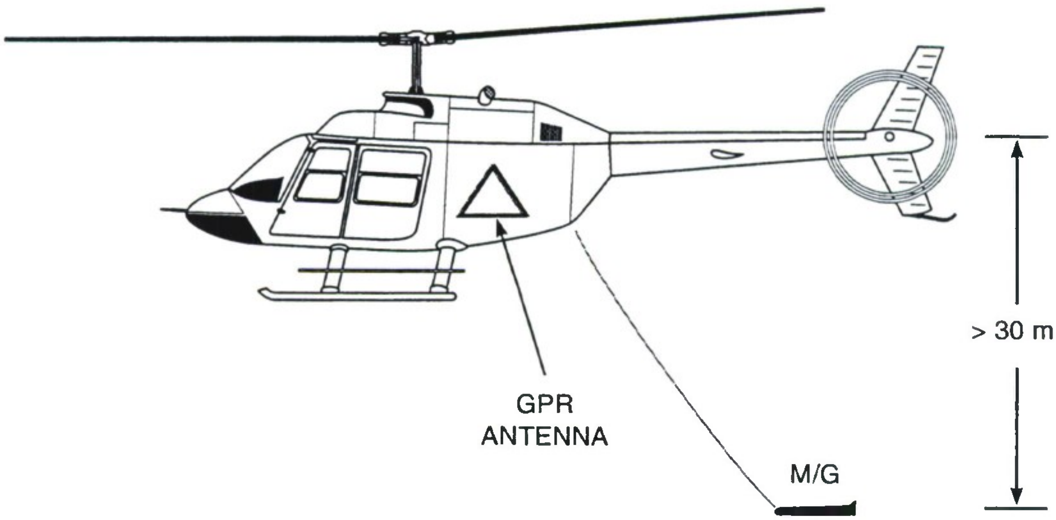


*Figure 7.1* *Cartoon illustration of proposed UXO-detection-stage sensor concept.*

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In addition to position tagging the location of individual ordnance, the detection-stage surveying should provide valuable input for subsequent survey and clean-up efforts. For this reason, we recommend that the ordnance position information be input as one parameter in a Geographic Information System (GIS) data base. Other parameters should include soil characteristics, depth of water table, local topology, and extent of foliation. Other parameters that would be highly desirable include human use, if any, and wildlife information, for example. An integrated data base that includes the aforementioned parameters will be invaluable in deciding how best to clean-up the land in question, whether there are site-specific risks associated with the clean-up effort, and what to expect from detection surveys of similar lands. In addition, some of the clean-up efforts may lag behind the surveys by several years or more; superficial terrain features may make ordnance maps difficult to interpret unless they are embedded in a more robust data set of geo-physical parameters.

### 7.1.1 Magnetometric, Gradiometric, and Induction Sensors

#### 7.1.1.1 Introduction

Magnetic sensors have been used to detect UXOs or mines containing ferrous or nonferrous metals [1-25]. In a typical UXO detection operation, a magnetic sensor is deployed at a small elevation above the ground surface; it scans an area to look for magnetic-signature anomalies; a UXO detection is declared when the strength of the anomaly exceeds a predefined threshold value. Magnetic sensors have been demonstrated to be the best sensors for detecting deeply buried UXOs [1].

Two of the primary concerns in deploying magnetic sensors for UXO detection are related to the target-to-clutter ratio (T/C) and the sensor resolution. As with the cuing-stage SARs, T/C measures the ability of the sensor to separate signals corresponding to UXOs from signals corresponding to background clutter or noise. Resolution refers to the ability to accurately pinpoint the locations of UXO.

Two state-of-the-art magnetic-sensor categories are currently in use for mine and UXO detections. The first sensor category is magnetometers and gradiometers. Whenever a ferrous-metal-containing object is placed in a background geomagnetic field, it causes perturbations in the local geomagnetic field. This perturbation is static and is often referred to as the secondary magnetic field. Magnetometers measure the secondary magnetic fields, gradiometers measure the gradient of the secondary magnetic fields. The second sensor category is that of active induction sensors, or induction sensors. (Passive induction sensors respond to changes in environmental parameters such as inductance or resonance frequency caused by the presence of metallic objects. They are useful only for surface or shallow-buried UXOs, and are not among the state-of-the-art magnetic sensors being used for UXO and mine detections.) An induction sensor contains a transmitter and a receiver. The transmitter transmits very-low-frequency signals, which induce eddy currents in ferrous or nonferrous metallic objects. These eddy currents, in turn, radiate secondary magnetic fields that are measured by the receiver.

### Magnetometers and Gradiometers

Both magnetometers and gradiometers are currently in use for the detection of UXO, which almost always contain ferrous metals. (Since gradiometers are basically arrangements of two or more magnetometers, the following technology descriptions will apply to both). There are four state-of-the-art magnetometer technologies: proton-precessing magnetometers, optically pumped magnetometers, fluxgates magnetometers, and magnetometers based on superconducting quantum interference devices (SQUID) [2]. A more complete summary of magnetometer technologies can be found in Reference 1.

Proton-precessing magnetometers and optically pumped magnetometers have large dynamic ranges, and are normally not used for constructing gradiometers. Proton-precessing magnetometers have sensitivity better than 0.05 nT, and the optically-pumped magnetometers have sensitivity better than 0.005 nT. Fluxgate magnetometers are based on solid-state technologies; they have large dynamic ranges and sensitivity better than 0.01 nT. Magnetometers based on SQUID technologies are the most sensitivite devices with reported sensitivities of $10^{-6}$ nT. Both fluxgate and SQUID-based magnetometers are used in constructing gradiometers.

Sensors using magnetometers or gradiometers will, in addition to detecting UXOs, also detect clutter from, for example, inhomogeneous soil-magnetic properties or discrete-ferrous objects. Although little has been reported on magnetic clutter in the open literature, some measured strengths have fallen in the range from 0.1 nT to 10 nT. [3-7] By comparing the sensitivity and noise levels associated with magnetometers to even the lowest clutter level (0.1 nT), one can conclude that UXO detection using magnetometers or gradiometers is clutter limited and not noise limited. It is difficult to quantify, in absolute terms, the relative performance of existing magnetometer or gradiometer sensors. Typical detection performances are usually summarized in a list of targets being detected (T/C greater than a specified threshold). False-alarm statistics are seldom discussed as part of the sensor performance primarily because of the sparseness of clutter data.

There are many UXO detection systems using magnetometers or gradiometers. One example is the Surface Towed Ordnance Location System (STOLS). [6,7] STOLS is equipped with seven cesium-vapor optically pumped field magnetometers mounted on a ground-based vehicle. Examples of magnetic-field surveys conducted with STOLS are shown in Figure 7.2, in which a number of UXOs or UXO simulants can be identified.

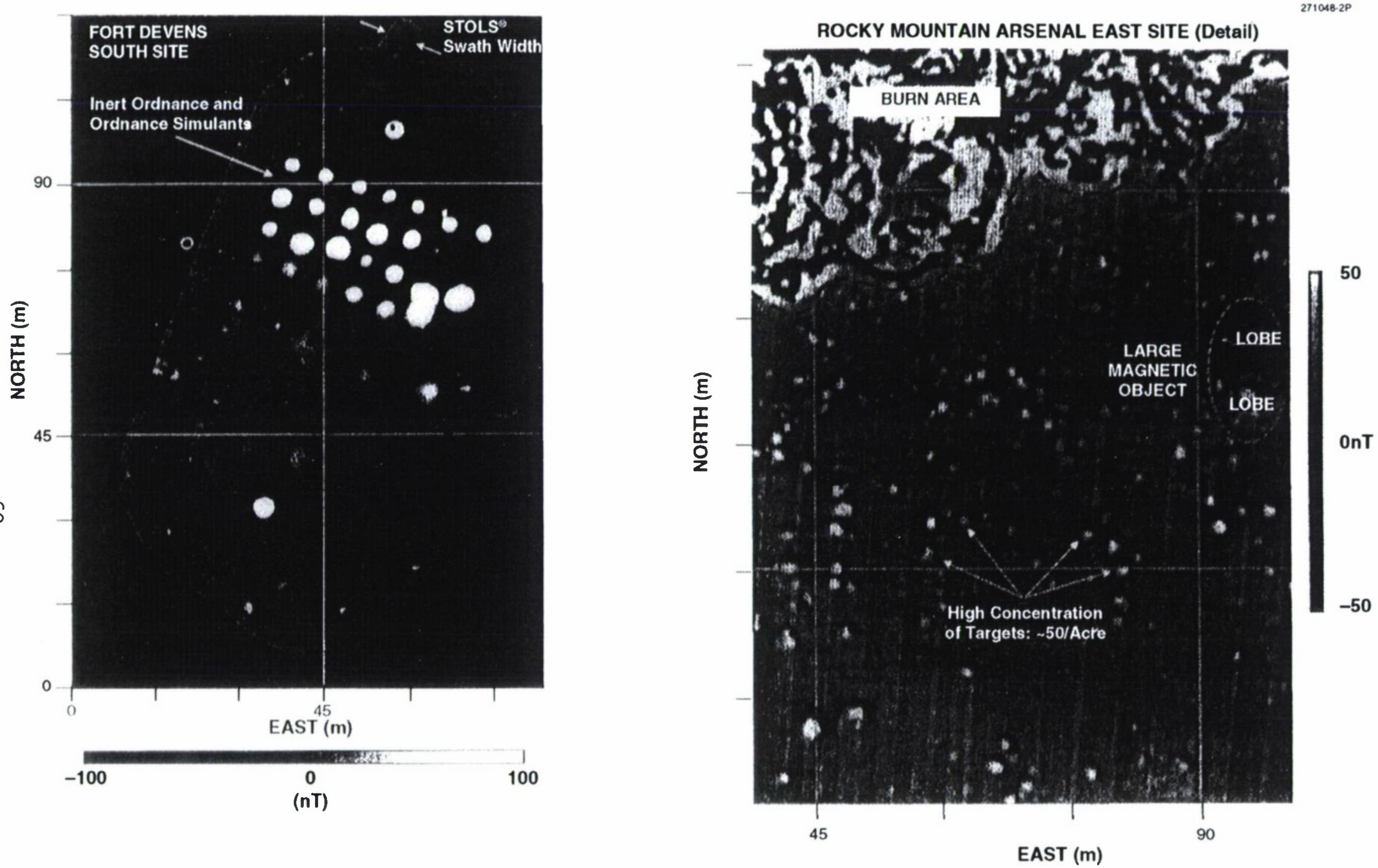


*Figure 7.2* *STOLS images corresponding to a magnetic field intensity survey. [6]*

Induction Sensors

Induction sensors are currently in use for both UXO and mine detection [1, 8-11]. The advantage they offer over magnetometric sensors is their ability to detect nonferrous-metallic objects; although this advantage is substantially more relevant for mine detection than it is for UXO detection.

Induction sensors are based on the principle of magnetic induction. A typical induction sensor has two coils. One of the coils is used to transmit low-frequency signals (500 Hz to 10 KHz); the other coil is used to detect the excited secondary-magnetic fields. To detect small UXOs or deeply-buried UXOs, the coils must be large to provide adequate sensitivity; unfortunately, using large coils degrades the spatial resolution necessary for the identification of shapes and sizes [1].

Clutter sources relevant to UXO-detection using induction sensors can be from sources such as geomagnetic-field variations from lightning, solar activities, industrial activities, etc., as well as from discrete metallic objects. Figure 7.3 shows the geomagnetic-field strength at various locations around the world, where $\gamma$ represents 1 nT [12]. Figure 7.4 shows a spectrum of geomagnetic-field strengths in the Antarctic continent [13]. These data show that there is a continuous decline in clutter level as the frequency increases; for frequencies higher than 100 Hz, the natural clutter background can be small, less than 0.1 pT/ $\sqrt{\text{Hz}}$. In addition, since the clutter caused by natural sources is usually of large spatial scale, its effect can be minimized by simultaneously measuring at a location near where the detection sensor is operating.

The limiting factor for induction-sensor-based UXO detection is not clear. Although there are significantly more clutter data available for induction-sensors than for magnetometric and gradiometric sensors, the typical detection performances are, again, summarized in a list of detected targets with almost no false-alarm statistics reported.

Induction sensors have been widely used for military mine-sweeping applications [11] because mines often contain little or no ferrous material and, hence, cannot be detected by magnetometric sensors. Induction sensors have also been developed for deeply buried UXOs [8,10], but little information on their detection performance is available.

### 7.1.1.2 Magnetic Sensor Deployment

For UXO detection, magnetic sensors are almost always deployed near the ground surface; they are either handheld or towed from ground or near-ground-based vehicles, such as trucks or helicopters. There are two reasons why magnetic sensors are deployed near the ground surface.

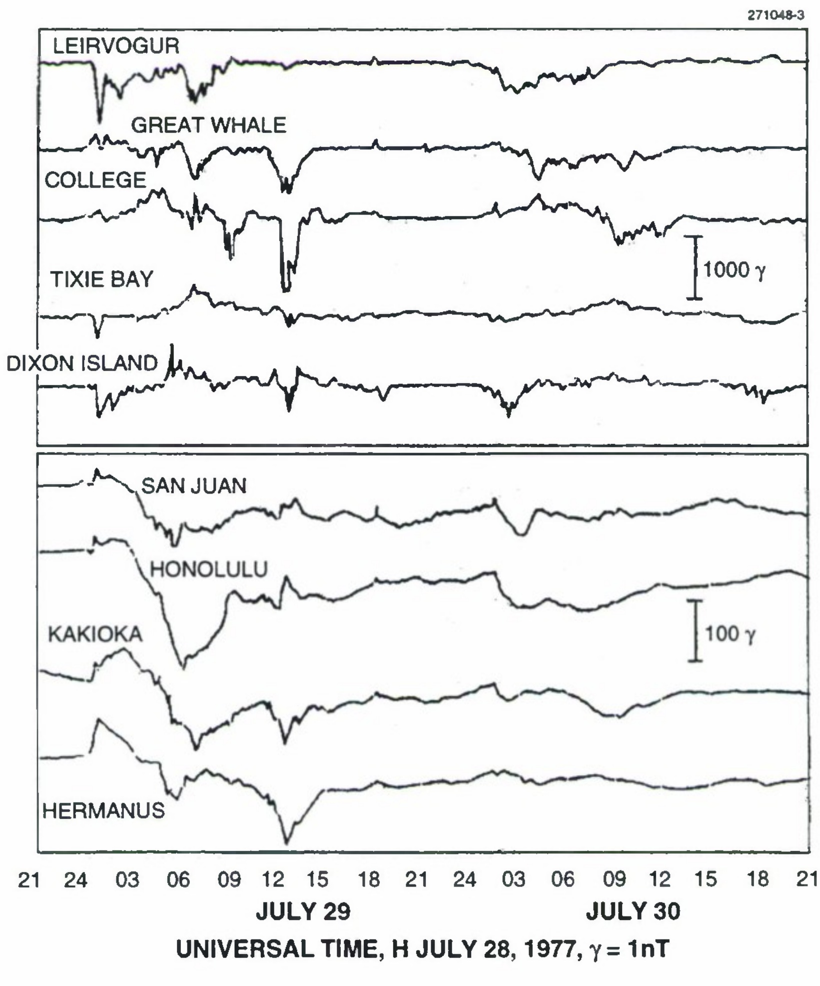


*Figure 7.3* *Temporal geomagnetic field variations at various location around the world. [12]*

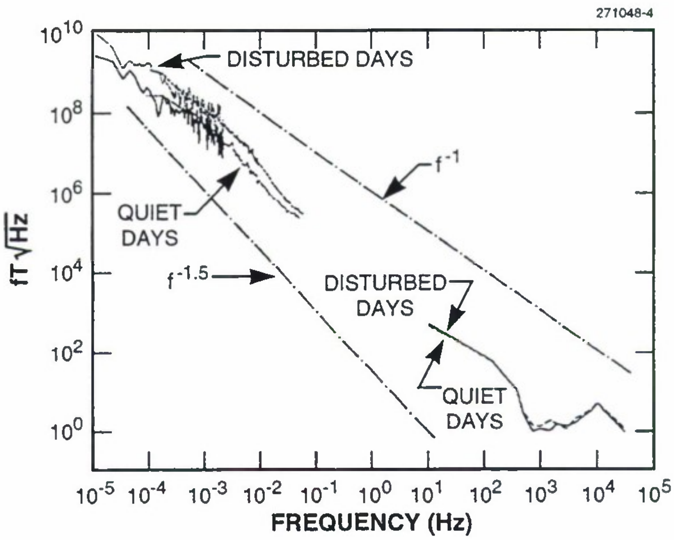


*Figure 7.4* *Spectrum of geomagnetic field in the Antarctic continent. [13]*

The first reason is based on UXO target signal strength (T). Magnetic sensors detect static or quasi-static magnetic fields induced by the presence of UXOs. The static and quasi-static magnetic fields suffer little or no soil attenuation; this is why magnetic sensors can be used to detect deeply-buried UXOs. However, the static and quasi-static magnetic fields decay at a minimum rate proportional to $1/r^3$ where r is the distance between the sensor and the target. Consequently, to maximize the UXO signal strength, the magnetic sensors must be as close to the target as possible. Unfortunately, the signal strength associated with ground-magnetic clutter also increases with proximity to the ground surface. As a result, there can be an optimum sensor elevation, which may be near the ground but not in direct contact with the ground, for which the T/C ratio is maximized. [4]

The second reason why magnetic sensors are deployed near the ground surface is due to resolution, which, for magnetic sensors, is related to the gradient of field strength. As an illustration, Figure 7.5 shows the secondary field strength of a ferrous sphere, in a uniform background magnetic field, as a function of position along a straight line path that travels over the sphere. The sensor detects the maximum-field strength when it is directly above the sphere; the field strength decreases as the sensor moves away, and the field strength is reduced to half of its maximum value when x~d, or when the lateral displacement is approximately equal to the sphere's depth. That is, the resolution of the magnetic sensor is a function of the range to target. Thus, in order to maximize the resolution, the magnetic sensor should be placed as close to the ground surface as possible.

Moving platforms, such as ground vehicles and helicopters, that are used to tow magnetic sensors usually have large magnetic signatures that can significantly interfere with the UXO signatures and prevent reliable detections. There are two methods commonly used to minimize this interference. The first method is to subtract out the signatures associated with these platforms from the combined target/platform signatures. This method requires accurate characterization of the signatures associated with the platforms, which is, in itself, a difficult task. The second method is to separate the magnetic sensors from the towing platforms. The helicopter cable-towed sensor is an example of this method.

#### 7.1.1.3 Recommendations for a Magnetic-Sensor UXO Detection System

As can be seen from the previous discussions of magnetic-sensor technology and the existing systems that are currently being deployed by the EOD community, there are many sensor choices that detect even deeply buried UXOs. Unfortunately, we do not feel confident recommending a specific sensor type at this moment because we believe that not enough data has been accumulated on clutter to adequately predict a sensor's performance under typical UXO-

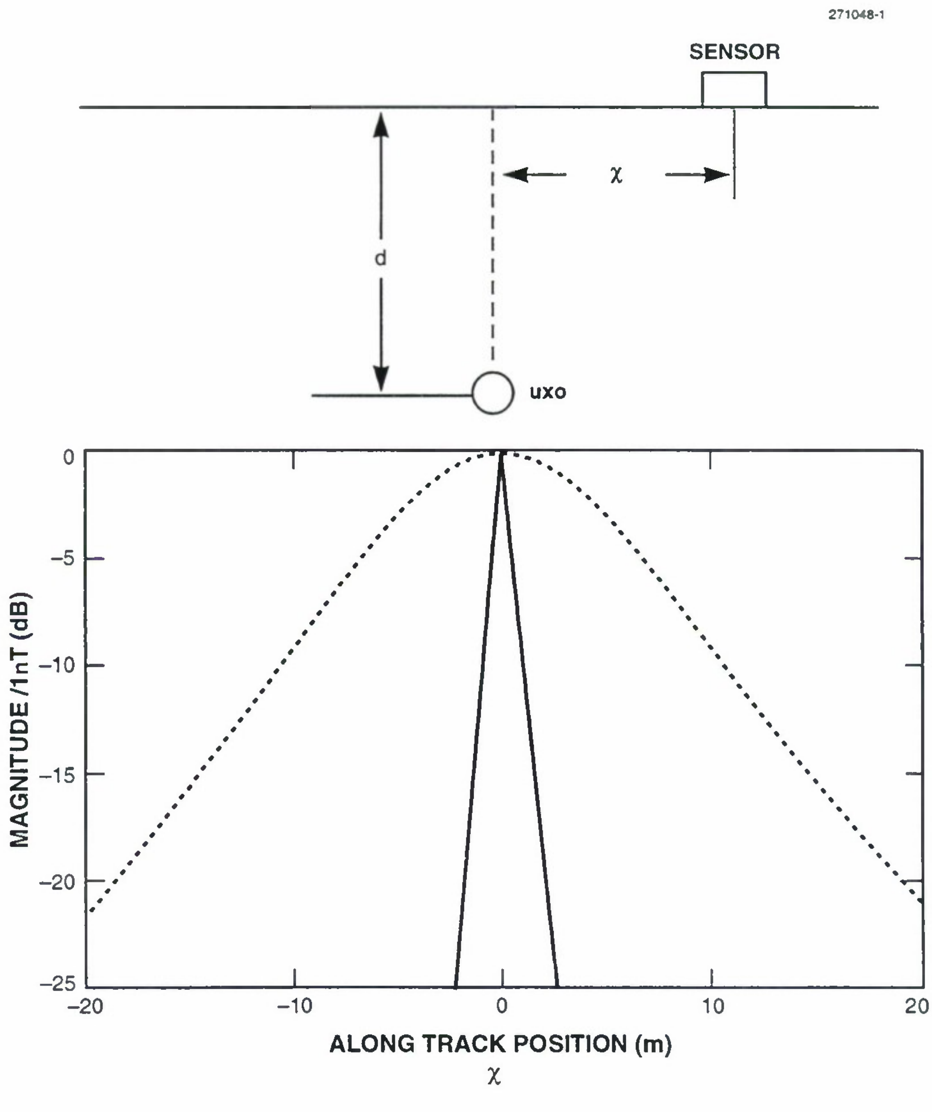


*Figure 7.5* *Secondary magnetic field strength as function of along track position.*

operating conditions. In the next section we shall discuss the critical phenomenology issues that must be addressed in order to make an informed choice about sensor construct. Given the mostly ferrous content of UXOs, we do recommend either magnetometric or gradiometric sensors, since they are simpler to operate and less prone to natural and man-made interference. If, however, nonferrous UXOs should be of interest, induction sensors should be considered.

We recommend that the eventual sensor suite be constructed to operate either from a helicopter-based cable-towed platform or from a vehicle-mounted boom. The helicopter choice is superior because of the greater area-coverage rate, as well as the high degree of isolation that can be acheived by separating the sensor from the helicopter. Unfortunately, a low-flying helicopter with a sensor platform dangling a few meters off of the ground may not easily access all of the lands that require detection-stage surveying, thus we suggest that a vehicle-deployed boom be considered as well. The boom is essential for both safety reasons, so that the vehicle does not have to drive directly over uninterroggated areas, and for isolation reasons, so that the field perturbation due to the vehicle does not interfere with target detections. The decision to invest in a vehicle-deployed sensor suite can only be made when an initial assessment of the lands that require surveying has been made.

#### 7.1.1.4 Technical Concerns and Recommended Investigations

There are a number of technical concerns that need to be investigated before the final system parameters can be defined. One of the most important and least understood concerns is the role of clutter on interpreting detection statistics. (Note that, in the magnetic sensor case, knowledge of the clutter is required to even help define the appropriate system, not just to assist in false-alarm reduction.) Other operational concerns include determining the optimum elevation above the ground surface, and estimating the maximum detection depth and resolution obtainable. Other important issues include UXO target signatures, signal-processing algorithms for T/C enhancement, and data-fusion algorithms for false-alarm reduction. We recommend that the following phenomenology and system issues be investigated.

1. Clutter data. Knowledge of background magnetic anomaly intensities is required to assess the predicted performance of a magnetic-sensor system. Experiments that measure background and noise characteristics at representative UXO sites should be conducted. Clutter should be examined for a range of elevations from ground-contact to tens of meters above ground in order to assist in defining the optimum sensor elevation.

2. UXO signatures. UXO target signatures as functions of ordnance size, orientation, and depth of burial must be measured. Signal strength and resolution as functions of range to target should be measured for some realistic operational scenarios using moderately

sensitive (e.g., optically-pumped) to highly sensitive (SQUID-based) magnetometers. It is expected that the results of investigations 1 and 2 will permit one to choose the optimum sensor type and configuration (magnetometric or gradiometric).

3. Platform interference. The effects of the survey platform on magnetic-detection ability should be assessed and means examined for minimization of this interference.

4. Image-processing algorithms. Image-processing algorithms are needed to detect small UXO signatures that may be near magnetic anomalies.

5. ATR algorithms for UXO detection. Even though the amount of lands to be surveyed is less than that in the cuing stage, total manual UXO detection is not practical.

#### 7.1.1.5 Existing Magnetic UXO Detection Systems and Programs

There are a number of magnetic UXO detection systems, including a few that have been deployed from helicopters or towed from vehicles. They include:

1. Geonex Aerodat's Helicopter Survey systems [26]: Aerodat has fielded a number of different cable-towed magnetic, gradiometric, and electromagnetic-induction sensors from a helicopter platform. Surveys have been conducted at, for example, INEL to survey ordnance and burn pits, ORNL to identify waste groupings and small ferrous objects, and JPG for UXO detection.

2. The STOLS system by GEO-CENTERS, Inc. [6,7]: This system uses total-field-magnetic measurements to find anomalies associated with UXOs. An array of seven cesium-vapor optically pumped total-field magnetometers are mounted on a platform and towed 10 feet behind a ground-based vehicle. The system can travel up to 20 mile/hour.

3. MUDSS system by NSWC, CSS and LORAL (see Appendix D): Although this system was designed for underwater UXO surveys, it utilizes a SQUID gradiometer towed from a surface platform in tandem with other acoustic and optical sensors. Some data-fusion algorithms have been implemented. A related airborne-magnetometer sensor has been proposed for UXO detection as part of the Fused Airborne Sensor Technology (FAST) system. [27]

### 7.1.2 Ground-Penetrating Radar

#### 7.1.2.1 Introduction

A ground-penetrating radar (GPR) is the second sensor type that we propose for the detection-stage system. By GPR, we refer to a down-looking radar system (as described in section 6.1.1) operating primarily in the VHF/UHF bands. GPR systems have been used for decades by the geophysical community to probe the ground to determine the underlying strata. Soil and rock layering and water-table depths have been determined by GPR probing. Utilities companies have used GPRs to find buried pipes, both metallic and plastic. Archaeologists use GPR to find buried artifacts and structures. Numerous other applications involving GPRs have been reported as well. [28,29]

GPR is a useful sensor when: (1) the soil is not exceedingly lossy, (2) the target or layer of interest has a high-dielectric-constant contrast with the surrounding or adjacent ground, (3) the target or layer is not excessively deep, and (4) the search area is not extremely large [30]. Quantifying the criteria stated above is a systems-analysis problem that has been performed for certain specific cases. [31,32] Fortunately, these criteria are largely met for the application of UXO remediation, which typically requires the detection of metallic targets that are mostly concentrated within 1 meter of the surface. Soil losses are often in the acceptable range for depths less than or equal to 1 meter, and the search area is not overwhelming if the GPR can be cued by other sensors or from information available from the site history.

To justify the claim that soil losses are often in the acceptable range we have computed expected attenuations for typical soils. Figure 7.6 is a plot of attenuation vs. soil conductivity with frequency and real dielectric constant as parameters [29]. Various types of ground constituents are indicated to show typical dielectric constants and conductivity values. VHF/UHF-band GPR should be able to detect targets at depths less than 1 meter for soils with one-way attenuations less than 40 dB per meter. GPRs typically have high-dynamic range, and excellent sensitivity when deployed close to the target.

As with magnetic sensors, the limiting factor in using GPR for UXO detection within the surface few feet is not so much attenuation, but clutter. In radar terminology the GPR problem is clutter-limited, not noise-limited. In contrast to magnetic sensing, however, the sources of clutter can include vegetation and other non-metallic objects. Three techniques have been developed to reject clutter; they are imaging, polarimetrics, and natural-resonance filtering. The rejection of clutter is such an essential part of a successful GPR system that we offer a brief explanation of each technique.

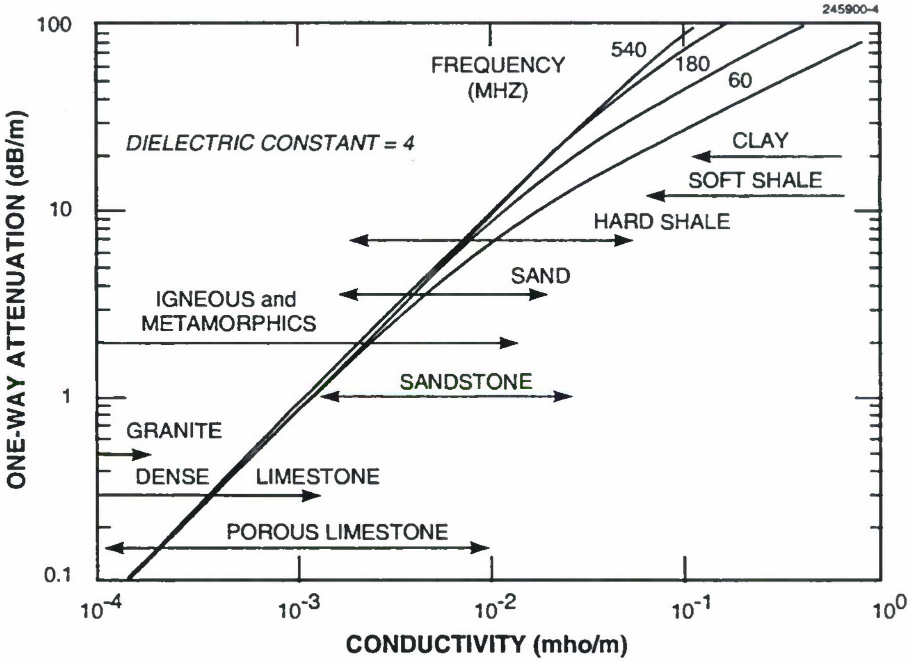


*Figure 7.6* *One-way RF attenuation due to conductivity losses versus conductivity at 1, 10, 100, and 1000 MHz. Horizontal lines show the range of conductivity of different materials.*

## Imaging

GPR has typically been used in a non-imaging mode, that is, the GPR is moved over the surface and, at each antenna position, a range profile is measured. The resulting data are then plotted and appear as a two-dimensional display. In fact, no coherent imaging in cross-range has been performed, so the plot represents power as a function of range for each antenna position; we refer to this representation as a real-beam plot. An example of a real-beam plot of a buried parasitic dipole (5 meters long and 2.5 cm in diameter) buried 0.5 meters in the ground is shown in Figure 7.7 [33]. Notice that the dipole return appears as a hyperbola in the real-beam plot.

The real-beam plot is to be contrasted with a coherently processed two-dimensional image, that is, a plot of power as a function of depth and cross-range coordinate. There are significant differences between the one-dimensional real-beam plot and the two-dimensional image. A point target in the one-dimensional plot appears as a hyperbola, as was mentioned above. A point target in a two-dimensional image appears as a point spread function, as shown in Figure 7.8. The main advantage of two-dimensional imaging is an increased target-to-clutter ratio because of the improvement in resolution in the cross-range direction. The improvement is approximately given by the ratio of the synthetic aperture length and the size of the real-antenna aperture. The maximum usable length of the synthetic aperture is given by the product of the range to the target and the real-antenna beamwidth. The maximum synthetic-aperture length is at least as long as the along-track dimension of the hyperbolic response in the real-beam plot. Target-to-clutter ratio improvements of 10 to 20 dB can be expected by two-dimensional imaging, assuming uniform volumetric clutter.

Just as two-dimensional imaging represents a significant improvement over one-dimensional range profiling, three-dimensional imaging is a significant improvement over 2-D imaging. A similiar quantitative improvement in target-to-clutter ratio can be realized by 3-D imaging. This implies that target-to-clutter ratio increases of 20 to 40 dB can be realized over one-dimensional range-profiling.

The tremendous increase in target-to-clutter ratio that results from coherent imaging results from the reduction in the volume resolution cell. The volume resolution cell in the 1-D case is an elliptical section of a spherical shell. The thickness of the shell is determined by the bandwidth of the signal, and the major and minor axes of the ellipse are determined by the antenna E- and H-plane beamwidths. The volume resolution cell in the 2-D case is a narrow rectangular strip section of a spherical shell. The reduction from an elliptical section to a narrow strip results from the synthesis of a one-dimensional array that produces a synthetic-fan beam. The volume resolution cell in the 3-D case is a small rectangular section of a spherical shell. The reduction from a strip to a small rectangle is due to the synthesis of a two-dimensional array, which produces a synthetic pencil-beam. The point spread function in 3-D is shown in Figure 7.9; notice that it is three-dimensional and represents the resolved volume in a 3-D image.

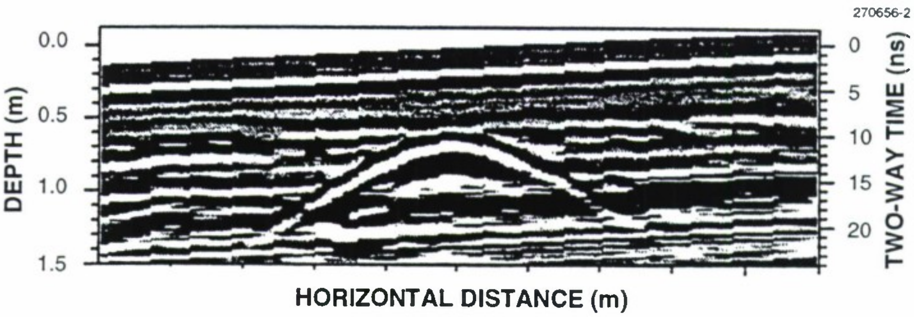


*Figure 7.7* *500 MHz antenna signal from 2.5 cm-diameter insulated rods (dipoles) buried 0.5 m deep at Yuma Proving Ground.*

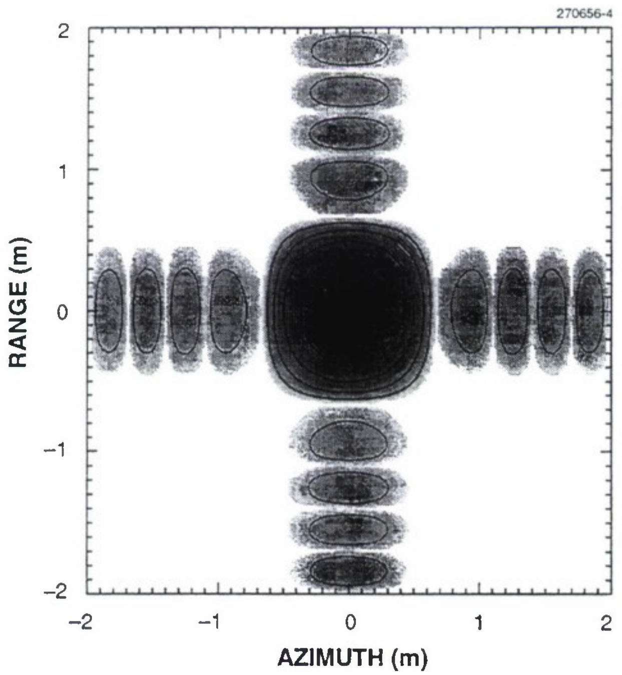


*Figure 7.8* *Two-dimensional point-spread function of 500 MHz bandwidth signal.*

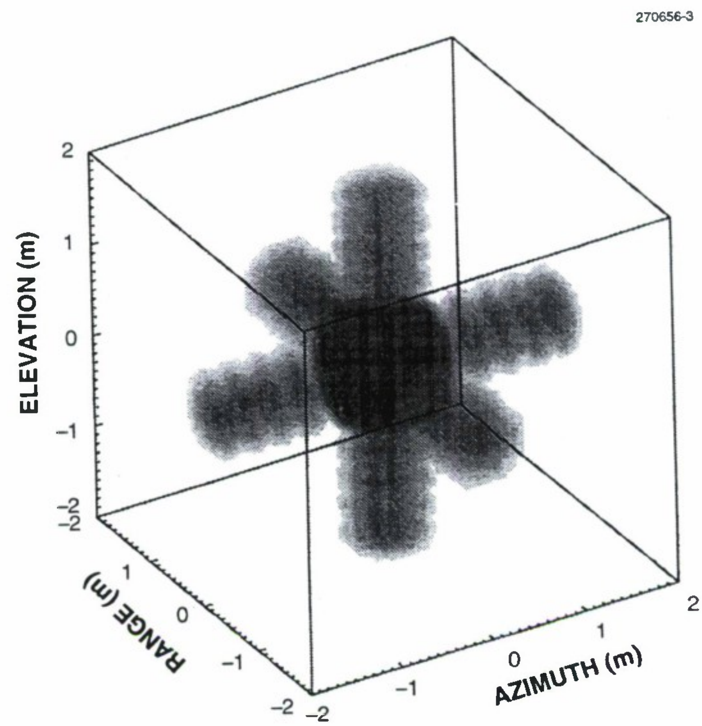


*Figure 7.9* *Three-dimensional point-spread function of 500 MHz bandwidth signal.*

The disadvantage of imaging over range profiling is the increased sampling requirement. This requirement implies that more data must be collected, data-collection times must be increased, motion-sensing is required, and the processing time is significantly increased. It is partly for these reasons that very little work on imaging has been done with GPR and we did not recommend it for the cuing stage platform, where high-area coverage was a requirement. An example of some very preliminary work on 3-D imaging with GPR has, however, been reported in Reference 34.

Polarimetrics

Clutter rejection can also be achieved by performing full-scattering-matrix measurements. Scattering-matrix measurements require that the radar be fully polarimetric. This means that the radar must be able to transmit one polarization and receive like and orthogonal polarizations and to repeat the process for the orthogonal transmit polarization. Of particular importance is the ability to measure the cross-polarized channels. These channels largely filter out the clutter associated with the air-ground interface, underground stratified layers, and rocks, since these objects tend to backscatter into the co-polarized channels. [35] UXO targets that are neither spherical nor plate-like will tend to backscatter some signal into the cross-polarized channels. Many UXO targets are quasi-cylindrical in shape (e.g., bombs) and will produce both co- and cross-polarized returns for most orientations.

The co-polarized channels will reveal the clutter quite clearly and will also show the target. Polarimetric algorithms can be developed based on the properties of the clutter and the targets to maximize the target-to-clutter ratios [36]. These algorithms also have the effect of reducing speckle in the imagery due to multiple-clutter-scattering centers within a resolution cell. The result of polarimetric processing is an optimized target signal in a smoothed background that improves detection performance.

Natural Resonance Filtering

Once potential targets have been detected, an additional stage of filtering is required to further reduce the false-alarm rate. This final stage of filtering requires more precise a priori information about the target set in order to separate the targets from the remaining clutter. Dimensional information about the expected ordnance and preferably ultra-wideband electromagnetic backscatter signatures of the UXOs obtained in an RCS range would be required. If the soil has been characterized, the perturbations in the signals of buried UXOs can be predicted [37].

The target signature of interest is its natural-resonance response. This is that part of the UXO target response that persists in time after the forced response of the target to the incident signal. More simply, the forced response of the UXO is dominated by its specular return and the natural response is its resonance response. The natural response can be modeled as a superposition of damped sinusoids. Each sinusoid is characterized by an attenuation constant and a natural frequency. Targets are identified by a set of complex numbers that define the attenuation constants and natural frequencies, which are determined by the target geometry and soil parameters. An example of the response of a buried structure to an incident electromagnetic pulse (EMP) is shown in Figure 7.10 [38]. The structure is an insulated dipole antenna, 104.7 meters long, buried 1.25 meters in a lossy dielectric half-space. The short-circuit current is shown as a function of time and strongly resembles a damped sinusoid. Some initial work on natural-resonance detection of buried cylinders and ordnance has been reported [39].

The detection of natural resonances requires very high signal-to-noise and signal-to-clutter ratios, which, in turn, require image data. The natural frequency of a target is a strong function of the target's length, and the technique works best on targets with large aspect ratios (length-to-width ratios) or equivalently high Qs.

#### 7.1.2.2 Recommendations for a GPR System

On the basis of both theoretical performance estimates and some experimental data, we suggest that a testbed-GPR sensor should be developed to be deployed with the magnetic sensor in the detection-stage suite. As discussed in section 7.1.1, the platform may be a helicopter (in which case the GPR would be mounted on the platform, not towed) or a ground-based boom-mounted system. The detection-sensor suite will survey lands identified during either the prescreen or cuing stages. Concurrently with sensor development, we recommend that techniques for sensor calibration and collection and processing of the resultant data be supported. The GPR sensor should

1. operate in a down-looking 3-D SAR mode,
2. cover the ultra-wideband VHF/UHF frequency range, and
3. be fully polarimetric.

The down-looking SAR mode should have adequate sampling for 2-D and, in some cases 3-D, imaging in order to maximize the resolution in the cross-range direction and increase the target-to-clutter ratio. We also recommend monitoring the 1-D results in real-time with a detector designed to detect hyperbolic trajectories. The VHF/UHF band is recommended because reasonably high resolution can be maintained with acceptable soil attenuation. (Note that lower frequencies suffer less soil attenuation but their reduced relative bandwidth degrades the obtainable resolution.) A fully polarimetric system is suggested to increase the target-to-clutter ratio and provide data for speckle-reduction algorithms.

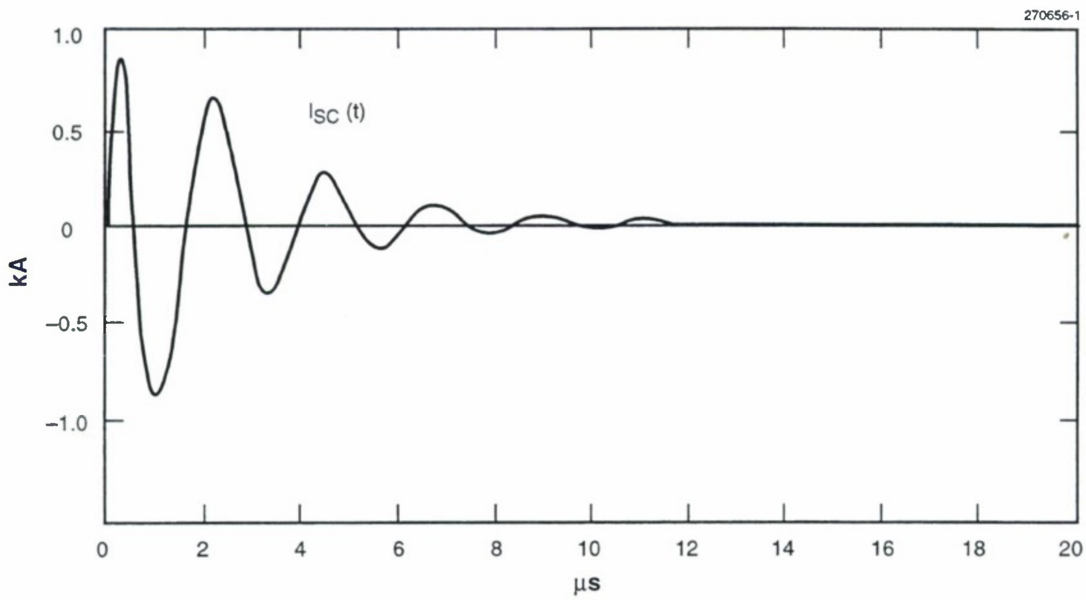


*Figure 7.10* *Shotr-circuit current response of a buried insulated dipole to a high-altitude EMP.*

It is also proposed that the GPR for the sensor suite be of instrumentation quality and efforts be made to calibrate the sensor at each data-collection site. Instrumentation-quality radars that are used to collect data to study radar phenomenology and target detection are generally calibrated sensors. The advantage of using calibrated sensors is that absolute-amplitude estimates of both the targets and the clutter are obtained. By measuring targets in different clutter environments, estimates of important phenomenological parameters can be obtained. Such parameters include dielectric constant, attenuation, volume-clutter coefficient, etc.. These are important parameters for assessing GPR performance.

We mention this feature specifically because GPR results are often presented without any calibration having been performed. Consequently, the results are of limited utility as they cannot be directly compared to results obtained with other sensors or even with the same sensor operated at other sites. To some degree, this has led to an (unfairly) low assessment of GPR's capabilities. Calibration is a difficult problem for ground-contact radars because the antenna input impedance is a function of the soil parameters, which vary spatially, and deploying calibration targets in the ground can perturb the medium significantly. For a near-ground system, such as would be deployed on a helicopter, the calibration of a GPR system is fairly easy.

Processing power will be critical to the successful exploitation of the data. The radar data will be high resolution, fully polarimetric data that needs to be imaged, co-registered with the magnetic sensor, fused, and analyzed. The end result of the processing should be high probabilities of detection and low false-alarm rates.

#### 7.1.2.3 Phenomenology Issues to be Investigated

Before we can begin developing the system described above, we must address several important phenomenology and systems issues. For the most part, the basic phenomenologies to be investigated in developing the GPR are identical to those described in section 6.1.1 for the cuing-stage SAR system. They were

1. clutter statistics,
2. UXO target signatures,
3. soil attentuation properties, and
4. RFI interference.

In addition, there are a few data-processing issues that are especially important for the GPR system that we propose. They are

1. Fast 3-D image processing. SAR imaging for GPR is computationally intensive because of the close ranges (and corresponding small swath widths) that result from a down-looking system. 3-D imaging places an additional burden on the processing since the imaging is performed over a volume. Back-projection processing has generally been used, which is not Fast-Fourier-Transform (FFT) based. Faster image-processing techniques than back projection that work well for large integration angles have been developed for airborne SAR applications. One such method, known as migration processing, has its origins in seismic processing. These techniques need to be applied to 3-D GPR imaging so that processing is not an overwhelming burden.

2. Polarimetric processing. Although polarimetric processing is a mature technology for radar applications, it has not been applied, to our knowledge, to the GPR problem. This is mostly due to the lack of fully-polarimetric GPR sensors. In order to successfully exploit the advantages that polarimetric processing can offer in target detection and clutter rejection, GPR-specific techniques must be developed.

3. Natural-resonance filtering. Although some work has been done on natural resonance filtering, it is preliminary and needs further development. This is especially true in false-alarm discrimination.

#### 7.1.2.4 Relevant Programs and Systems

The U.S. Army Environmental Center (USAEC) currently manages the UXO Clearance Technology Program. USAEC has designated the Naval Explosive Ordnance Disposal Technology Division (NAVEODTECHDIV) as the technical lead for this program. A total of 17 projects are currently being conducted under the UXO Clearance Technology Program . Three of the projects are using and developing technologies similar to our recommended system. These programs are described by USAEC as follows [40]

<u>Subsurface Ordnance Characterization System (SOCS)</u>

The objective of the SOCS project is to demonstrate a multisensor data-acquisition system and use it as a test bed to evaluate emerging sensor technology for UXO detection, identification, and localization. SOCS simultaneously acquires data from a variety of mounted UXO detection sensors. The system's flexible, open architecture enables it to readily use different sensor technologies. The number and types of sensors used depends on the individual sensor capabilities and limitations and the interference characteristics between sensor types. SOCS allows data to be collected from different sources in a single survey, thus avoiding the time and cost of surveying an area several times with different sensors.

SOCS consists of an autonomous tow vehicle, a platform, a data-acquisition system, navigation equipment, and detection sensors. The SOCS design minimizes magnetic-eddy-current interference among the ground penetrating radar (GPR), magnetometers, and platform by selecting appropriate materials, shielding GPR antennas, and isolating structural members. In 1995, SOCS was demonstrated using one GPR and four magnetometers at Tyndall AFB in Florida. Addtitional sensors and combinations of sensors will be demonstrated in 1995 and 1996 at JPG.

Airborne Ground Penetrating Radar (AGPR)

AGPR is currently being used by the private sector to conduct site surveys to detect buried targets (UXO and others), changes in soil strata, and changes in topography. The AGPR project was established to determine the technology's ability to define the boundaries of UXO-contaminated sites and the concentration or extent of contamination. The project involves researching the capabilities of AGPR, determining which privately developed system can best detect subsurface UXO, and optimizing AGPR capabilities for UXO detection. NAVEODTECHDIV, Battelle, and The Ohio State University Electroscience Laboratory have examined AGPR's potential for detection, identification, and localization of subsurface UXO. AGPR analyses were performed in March 1993 and December 1994. A technical report documenting the findings of these analyses was completed in April 1995. The report identifies various types of modifications that will be necessary for existing AGPR systems to function optimally for UXO detection.

Advanced Real-Time Imaging for Synthetic Aperture Radar (SAR)

The purpose of this project is to use an existing, hand-held GPR system to determine the best image-processing routines for detection, identification, and localization of buried UXO. The system will use SAR processing to provide better resolution for target localization. This effort is being performed by Metratek using its Model 200 GPR system. The Model 200 system has interchangeable radio-frequency heads and uses wideband, high-resolution, step-chirp imaging radar technology as it applies to GPR. The autofocus SAR software will be used to determine the depths of targets and can provide target shape images to expedite target idenfification.

Metratek has researched past work on hand-held GPR systems and has performed initial studies and tests of the radar system to be used in this project. Research performed to date includes radar performance analyses, antenna design and evaluation, radar cross section measurements of land mines at three different bandwidths, imaging of buried land mines and culverts, and development of three-dimensional imaging software that provides detailed images of subsurface objects. Tests will be performed to fine-tune radar instruments and processing routines at the NAVEODTECHDIV Magnetometer Test Range in Indian Head, Maryland.

Steel Crater

The Steel Crater program is sponsored by the Defense Intelligence Agency Central MASINT Office and managed by the U.S. Army Research Laboratory. Airborne and ground-based standoff ground-penetrating-radar tests have been and are currently being performed. Specifically, tests of both surface and buried objects have been conducted at Yuma Proving Ground (YPG). The airborne systems that have been tested to date have all used side-looking SAR sensors. [41-45]

One ground-based sensor that participated in the first YPG test and in a variety of other controlled experiments is the Rail SAR [46,47]. This system used a 30-foot long rail mounted on top of a 40-foot scissor lift. The antenna was moved along the rail by a stepper motor to form the synthetic aperture.

A ground-based sensor known as the "Boom SAR" will also be used in upcoming YPG tests. The Boom SAR is based on a fully polarimetric impulse radar [48] that is mounted on a self-propelled, 150 foot boom lift. The boom lift is driven with the main and tower booms fully extended vertically while the radar collects SAR data. The Boom SAR has the largest percentage bandwidth (192%) of any instrumentation or operational radar; the spectrum of the transmitted impulse is from 40 MHz to 1040 MHz.

The Steel Crater Program has emphasized understanding the fundamental phenomenology associated with standoff ground-penetrating radar. Several sensors have been used to collect data on buried targets and the surrounding clutter. The data has been calibrated, processed and analyzed. Electromagnetic models have been developed to understand the data and advanced signal-processing algorithms have been applied to improve target features [49].

## 7.2 SENSOR FUSION AND DATA PROCESSING

Since we are proposing that the magnetic and the GPR sensors be deployed from a helicopter or boom-based platform, and we require that the magnetic sensor be separated from the platform, the task of image registration will be especially challenging. As we envisage the detection-stage sensor suite, the down-looking GPR will reside on the helicopter platform and the magnetic sensor will be towed some tens of meters below the platform to minimize interference. Co-registering the magnetic and GPR sensor data will be difficult and will require investigation.

There are three factors that will complicate this effort. The first, as mentioned above, is the physical seperation between the two sensor types. The second is the position-stability of the cable-towed magnetic sensor; this problem can be addressed by including motion-sensing-instrumentation on the towed platform. The third complication is due to the vastly different resolutions obtainable by the two sensor types, which can be simplified by co-registering at the detection level. Other features, such as measurement time and environmental interferences must be considered and, in fact, will contribute to the design requirements for the individual sensor types.

The sensors have been chosen to represent two overlapping capabilities in terms of both target and clutter rejection. For example, the magnetic sensor can be expected to detect most ferrous objects buried to depths of a few feet; it will be affected by both naturally occuring and man-made magnetic anomolies. The GPR can be expected to detect metallic and non-metallic buried objects and will be strongly affected by vegetation and non-metallic clutter. High-confidence detections by the magnetic sensor do not necessarily need to be corroborated with the GPR but it is recommended. Areas where the magnetic sensor shows low confidence detections or ambiguous results should be imaged with the GPR in 2-D mode and, if necessary, additional data collected in 3-D mode.

Little work has been conducted in the area of data fusion of magnetic and radar-based sensors, although systems have been proposed [for example, 27] and some post-mission processing has been attempted on existing data. [24] One program that we are aware of is called Magnetic/Acoustic Detection of Mines (MADOM), which succcessfully demonstrated fusion of gradiometric and sonar sensors that were separated by several meters. [see description and references in Appendix D]. The data fusion architecture employed in MADOM and other programs should be reviewed for its applicability to magnetic and GPR sensor-data fusion. We suggest that the development of data-fusion algorithms be given a high priority in this sensing stage.

## 7.3 PAYOFF/RISK ASSESSMENT

### 7.3.1 Potential Payoff

The primary payoff that results from the detection stage is the large data base that will be accumulated on exact positions of surface and buried UXO. This information, in conjunction with site-specific characteristics and sensor performance data, will directly assist in remediation efforts and ongoing survey efforts.

### 7.3.2 Applicability

There are many conditions under which the detection-stage platform will optimally operate and several under which it is inappropriate. Some of the concerns surrounding implementation of this stage are

1. Deeply buried targets will be very hard to detect. This may drive the potential land use, and certainly the remediation procedure. If a majority of the UXOs are deeply buried, then the helicopter-based system will less useful.

2. Not all sites are amenable to GPR. Under some soil conditions, e.g., those with high moisture content, GPR may be ineffective.

3. Airborne surveys may not always be possible. The helicopter system is preferred but excessive ground foliage or unusual site conditions may require the use of a land-based platform. If a land-based platform is deployed, there is both a reduction in coverage rate as well as an increase in risk to the sensor platform.

3. False-alarm rates must be low to reduce remediation costs. The key to reducing false alarm rates is the use of data fusion, which, for the magnetic and GPR sensors, is at a low level of development.

### 7.3.3 Issues Associated with Risk Assessment

Table 7.3.1 gives our preliminary assessment of the the risks associated with the research and development of a detection-stage sensor suite.

Table 7.3.1
Research and development risk assessment

| R&D EFFORT | RESEARCH RISK | COST | BENEFITS |
|---|---|---|---|
| Evaluate sites for airborne survey suitability | Low | Low | High |
| Magnetometer System | | | |
| Clutter Statistics | Low | Moderate | High |
| UXO Signatures | Low | Moderate | Moderate |
| Interference | Low | Low | Moderate |
| GPR System | | | |
| Fast-3-D image processing | Moderate | Moderate | High |
| Polarimetric processing | Low | Low | High |
| Natural resonance filtering | Moderate | Low | High |
| Registration Issues | Moderate | Low | High |
| Sensor Integration and Data Fusion | Moderate | High | High |

### 7.3.4 Impact on Health and Safety Risk Model

The probability of detection in the detection stage is less critical than the probability of detection of the cuing stage in assessing the overall performance of the system. Since the detection-stage sensors were cued to a site, there will typically be a cluster of UXOs present. For sites actively undergoing remediation, it is likely that the detection sensor suite will be used multiple times over a given area, therefore improving overall system-detection rates. Therefore, it can be argued that the overall cleared probability of detection will be slightly greater than the detection-stage probability of detection alone. The primary benefit that results from a high probability of detection is the reduced risk to the safety of the remediation workers.

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# 8. CLASSIFICATION STAGE

## 8.1 SYSTEM OVERVIEW

Once probable ordnance are located and mapped in the detection stage, one can use those maps to facilitate the clean-up process or to make informed decisions about appropriate land use. If one decides to clean-up an area that has been mapped for UXO, one has little choice but to conduct that clean-up in much the same manner as is currently done. Each ordnance must be carefully removed or excavated and trained personnel must be deployed whenever there is a suspicion that an ordnance still poses a hazard. In contrast, if one knew a priori which ordnance were hazardous, one could remove those items and simply rake or bulldoze the rest of the affected area. Thus, we propose a classification stage whose primary function is to distinguish those ordnance that pose a human or environmental hazard from those that do not. Unfortunately, the technology to achieve this design goal is less mature than those described in the cuing and detection stages. We therefore make a recommendation that appears, at this point, to have the highest likelihood of meeting our requirements, but that will require some research and development to offer a fieldable sensor. We propose that the classification-stage sensing system:

— utilize a ground-based platform that may operate concurrently with or independently of the detection-stage sensing system,

— consist of a thermal-neutron activation sensor that detects the presence of (at least) nitrogen, a primary constituent of explosive materials.

We are not aware of any explosive-sensing techniques that can offer standoff detection of a targeted ordnance; therefore, we recommend that the classification sensor be deployed on a ground-based platform. For this application, remotely operated vehicles offer the safest means of accessing the ordnance, although an operator-controlled vehicle with a standoff boom could probably be designed at minimal hazard.

### 8.1.1 Introduction

Although there a few techniques that have been proposed, and some cases developed, for explosives detection, we feel that thermal neutron activation (TNA) offers the greatest promise as a chemically specific, potentially fieldable sensor. In Figure 8.1, we show a depiction of the operating principle behind TNA. Thermal neutrons incident on an explosives-containing target activate nitrogen, which is a primary component of TNT, the most widely-used military explosive. The thermal neutrons are typically generated by a radio-isotope source, such as Californium-252

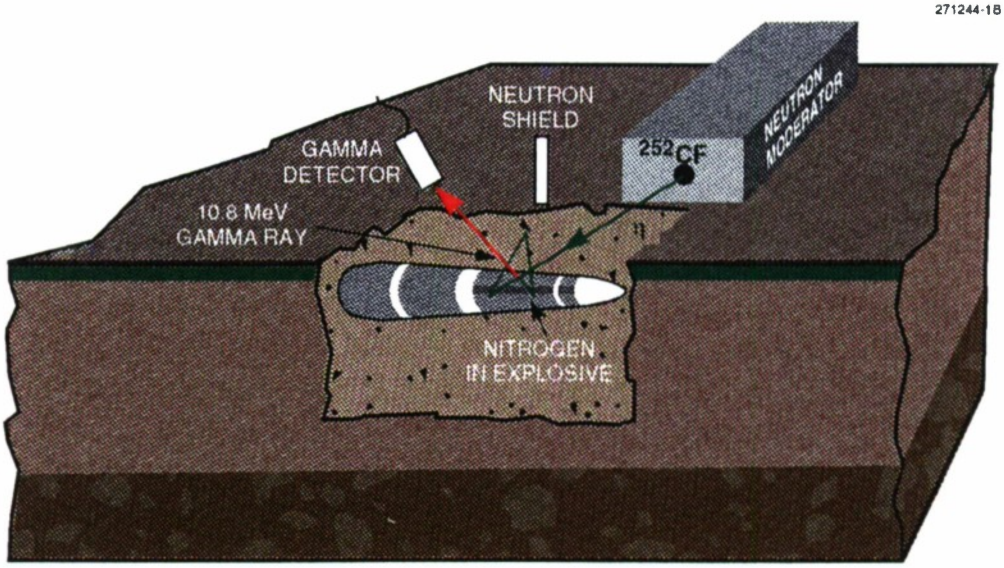


*Figure 8.1* *Schematic illustration of operating principle behind thermal neutron activation applied to explosives (nitrogen) detection.*

(Cf-252), whose neutron energy is reduced by a moderator such as polyethylene. The nitrogen decays by emission of a characteristic gamma ray of energy 10.8 MeV, which is then detected by either NaI(Tl), $BiGeO_4$, or high-purity Ge detectors. Thus, detection of the backscattered gamma emission is used to infer the presence of high concentrations of nitrogen. Since explosives have a nitrogen content ranging from 15 - 40% by weight and even heavily fertilized soil contains less than 0.1% [1], background interference from soils does not seem to pose a large problem for this sensing technique.

### 8.1.2 Basis for Recommending Thermal Neutron Activation Sensors

Most of the research in this area has been driven by the FAA for the specific application of screening luggage and cargo for explosives. In both the airport security and unexploded ordnance applications, the requirement is to detect hidden quantities of explosives noninvasively and with a high probability of detection. Several prototype TNA explosive-detection systems have been installed in airports worldwide and approximately 1 million pieces of luggage have been processed through these systems. [2] Results have been encouraging enough that a National Research Council Commitee on Commercial Aviation Security has recommended continued support for refinement of the devices at a high-priority level. [3] The concept may offer even more promise as an explosive-ordnance-detection technique because many of the limitations cited in the airport tests are not relevant to ordnance detection. For example, some cargo-inspection limitations mentioned in the NRC report include

- system detects only nitrogen,
- sensitivity degrades as explosive quantity decreases,
- high-false-alarm rate,
- uses radioactive source, and
- cannot be used on people.

The first limitation is a problem in aviation security because of the large numbers of explosives, such as acetylene precursors, fuel/air bombs using olefin oxides, perchlorate or chlorate salts as oxidizers, or self-igniting systems such as alkali and boranes, that contain little or no nitrogen. [4] The second limitation, poor sensitivity to small quantities, is of concern because of the way in which explosives are often distributed in luggage; for instance, they may be in sheet or pellet form distributed over a large container. The airport TNA systems have very poor spatial resolution and cannot, therefore, distinguish low levels of explosives that are widely distributed. False alarms result primarily from non-explosive nitrogen-containing items such as polymers with an amide or urethane structure or proteins (meats and cheeses, for example). [5] The false-alarm rate is high (about 18-20%) partly because of the high baggage screening requirements (10 bags per minute); if the speed requirement is relaxed, the false alarm rate can also be reduced. [6] The concern over use of radioactive sources is that some activation of the luggage may occur, resulting in a low-level hazard to handlers and possibly even luggage owners. The concern that TNA cannot be used on people is a valid one for airport security but not relevant to ordnance detection in any circumstances that we can envisage.

There are, however, some limitations that are important for the UXO applications. Most notably, the size and complexity of these airport-screening systems do not lend themselves to field use. (A typical footprint for a luggage screening system is 12m x 7m, which includes an X-ray machine as well). Two field-portable TNA-based systems have been developed, however, and have been demonstrated for mine and ordnance detection. One system, by SAIC Canada, has been developed to be incorporated on the Canadian Department of National Defence's Improved Landmine Detection Project (ILDP). [1] This project will deploy various sensors on a remotely operated all-terrain vehicle; the SAIC TNA sensor uses a Cf-252 source and high sensitivity, low-resolution detectors. The device claims the ability to detect a 500 g mine buried to depths of 15 cm or less in under 10 s.

A second fieldable system is the Portable Isotopic Neutron System (PINS), developed at the Department of Energy's Idaho National Engineering Laboratory (INEL). This system ,which uses a Californium 252 source, was originally designed to sense nuclear, biological, and chemical warfare agents, and does so by examining the backscattered gamma-ray spectrum for elemental signatures of the constituent compounds. [7]. The system is vehicle portable and has been tested on surface UXO at both the Tooele Army Depot in Utah and the former Navy Testing Range at Idaho Falls. [8] In field trials, the system has successfully detected nitrogen in high-explosive shells; in addition, iron was detected from the shell casings, which may offer an additional clutter discriminant as well as a built-in calibration.

### 8.1.3 Science and Phenomenology Issues to be Addressed

There are a few concerns that must be investigated in order to develop a TNA system that could be easily fielded by EOD personnel and satisfy the requirements of our proposed classification sensor. They are

- utility for subsurface UXO,
- time required to evaluate ordnance, and
- sources and detectors.

The major constraints to deploying TNA on subsurface UXO are the attenuation and interference of the intervening soil. Thermal neutrons of the fluxes available from a portable source will probably not penetrate soil more than a couple of feet and even less if the soil is moist.

It has been suggested, however, that instead of moderating the neutron energy as it exits the source, one could let the soil act as the moderator. [9] This technique would actually work better in wet soils (hydrogen moderates neutrons very effectively) and may permit greater penetration depth than externally moderated neutrons would permit. Unfortunately, without extensive soil characterization, the backscattered gamma signal would be essentially uncalibrated. Thus, one area of research should address soil penetration as a function of source characteristics and soil features.

A second consideration in sensing subsurface UXO is the potential for background interference from other nitrogen-containing targets, such as fertilizer and animal carcasses. Although the fraction of nitrogen in well-mixed fertilized soils is low, the possibility exists that clumps of fertilizer, which can be 35% nitrogen by weight [10], may be found that mimic the size and features of UXO. We suspect that the amount of UXO-contaminated land that is also actively fertilized is small, and we also point out that one is probably free to interrogate suspect lands in mid-winter or at the nadir of the fertilizing season. A second interferent may come from animals, whose wool or hair contains approximately 20% nitrogen. Once again, we suspect that the incidence of buried animals in a UXO field is not large, but a system such as PINS, which can detect both iron and nitrogen, may lower the false-alarm rates substantially. We suggest that some research be devoted to establishing the magnitude of interference from other nitrogen sources for typical scenarios of interest in UXO sensing.

The second concern, evaluation time, is more a function of the technology than the environment, and is intimately connected with the third concern, sources and detectors. The dwell time for characterization of explosives is primarily a function of the strength of the neutron source: large sources require bulky housing and shielding but are fast; wheras portable isotopic sources can require tens of seconds to tens of minutes to evaluate an ordnance. Compact, high-flux neutron sources will reduce the effect of soil attenuation and increase the speed of ordnance evaluation, but greater care will have to be taken in shielding the detector from the resultant increase in neutron backscatter. Similarly, detector sensitivity and temporal response will dictate how long one must integrate to conduct an unambiguous evaluation of an ordnance; thus, new detector types and geometries may also enhance the performance of portable TNA sensors. Another consideration in choosing detectors is the resolution. Scintillation detectors, such as NaI, are efficient and relatively inexpensive but do not have the resolution required to distinguish the nitrogen gamma emission peak at 10.8 MeV from potential interferents (such as the emission of silicon at 10.6 MeV). High-purity Ge detectors are expensive but offer the ability to conduct highly resolved gamma spectroscopy, such as is conducted by the PINS system. [11]

Finally, we mention that, in order to justify the development of a classification stage, some effort should be expended on establishing the hazard potential of representive ordnance. For newer ordnance, where dud rates are specified and well-known, this should be a relatively easy task. For older ordnance, however, it will be more difficult, and ongoing and past remediation efforts will have to provide the necessary data.

### 8.1.4 Key Players in TNA Sensing

There are not many programs developing field-portable thermal-neutron-activation systems; as mentioned earlier, those systems at the highest stage of development seem to be the Canadian ILDP sensor by SAIC and the PINS sensor developed at INEL.

## 8.2 SENSOR FUSION AND DATA PROCESSING

Since we propose only one sensor type for the classification stage, concerns pertaining to sensor fusion are not especially relevant. It will be important, however, to consider how the ordnance-position data that was accumulated during the detection stage will be used to direct the classification-stage platform. For example, we proposed "marking" the location of ordnance using GPS inputs and deriving maps that are used as inputs to a GIS data base. Those maps must then be used to direct the TNA sensor to the pre-determined ordnance-position locations, where it must evaluate each ordnance for explosive potential. Such direction could be provided to the navigation system of a remotely-piloted vehicle, for example. Since the GPS-position accuracy can be affected by many factors including weather, number of satellites in view, and terrain variability, a back-up detection system, such as an on-board magnetometer, may be warranted to ensure that the platform is hovering over suspect ordnance. If this is done, then it will be important to shield the magnetometer from the vehicle and TNA sensor equipment.

More important is the role of data processing in interpreting data collected by the TNA sensor. We assume that the users of such a system would like near-real-time processing capability. For example, after a vehicle-mounted sensor has interrogated a given patch of ordnance, the data are examined and explosive ordnance are "marked" in the GIS data base, while the sensor is still in the field. If there are any ambiguous data, the sensor can be re-deployed to the ordnance in question and the ambiguity resolved. A superior mode of operation would be to relay the data to the vehicle operator as they are collected so that the operator can decide when to evaluate a particular ordnance more closely. In either case, we suggest that the process of making a positive identification of explosive ordnance be as automated as possible. In general, an evaluation should be considered positive for explosive ordnance when both ferrous or non-ferrous metals are found simultaneously with a nitrogen signature substantially above background. This type of AND target recognition should serve to reject those signals from either inert ordnance, metallic clutter, or explosive residue in soil.

## 8.3 PAYOFF/RISK ASSESSMENT

### 8.3.1 Potential Payoff

The payoff for the classification stage is potentially large. Not all UXOs represent an explosive hazard, although the explosives may have leaked out and become an environmental hazard. The payoff for this stage is a function of the relative number of hazardous UXOs compared to the total number of UXOs; as mentioned earlier, this fraction may be about 10%. If a remediation effort is undertaken, the speed of the remediation can be increased with a corresponding reduction in the cost.

### 8.3.2 Applicability

For the classification phase to be an effective means of reducing remediation costs several conditions must be present:

1. The probability of correct classification must be very high. If the system is not sufficiently reliable, the overall system performance will suffer.

2. If the classification system is used to aid in remediation efforts, the probability of correct classification must be sufficiently high that during remediation not all UXOs are considered dangerous.

3. A significant fraction of UXOs are considered inert. If most of the munitions are still dangerous or are a significant environmental hazard, then the munitions must all be removed.

### 8.3.3 Issues Associated with Risk Assessment

Table 8.1 is a summary of the estimated research and cost risk in supporting the development and evaluation of a classification-stage sensor suite.

Table 8.1
Research and development risk assessment

| R&D EFFORT | RESEARCH RISK | COST | BENEFITS |
|---|---|---|---|
| Estimate fraction of hazardous ordnance | Low | Low | High |
| TNA Sensor Technology | | | |
| Soil characteristics | Low | Moderate | Moderate |
| Interferents | Low | Low | Moderate |
| Sources and detectors | Moderate | Moderate | Moderate |

### 8.3.4 Impact on Health and Safety Risk Models

The risk concerns with this stage are similar to those for the cuing phase. The primary safety concern with this stage is the decision not to remediate or to declare an ordnance "safe". If such a declaration is falsely made in an area slated for clean-up, it can directly impact the safety of the remediation effort.

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# 9. SUMMARY

We have recommended a general systems approach to UXO sensing. A four-stage structure is proposed in which the large problem of UXO sensing of potentially-contaminated DoD lands is broken down into smaller, more manageable problem areas. We have structured the sensing requirements into stages, where different sensor technologies would be deployed within each stage to meet different survey requirements. The four stages are

- Prescreening,
- Cuing,
- Detection, and
- Classification.

The prescreen stage uses information from site histories as well as intended land use to identify a subset of potentially-contaminated lands that will require surveying. The cuing stage offers rapid coverage of surveyed lands, with the goal of identifying fields of surface and shallow-buried UXO. The detection stage provides a means for detailed surveying of suspect UXO fields to depths of up to a few feet. The classification stage offers a means of distinguishing inert ordnance from ordnance with explosive potential.

The result of a preliminary systems analysis has led us to recommend a few promising technologies for the above sensing stages. They are

<u>Cuing:</u>

- an airborne platform with onboard differential GPS and INS for accurate navigation and positioning,

- a dual-band (X-band and UHF) synthetic aperture radar (SAR) sensor to detect surface and shallow-buried ordnance,

- an electro-optic sensing system that includes passive detection of two infrared bands and active detection of one visible to near-infrared band for detection of surface and shallow-buried ordnance and clutter characterization.

- sensor-fusion techniques that take advantage of each sensor type's complementarity as well as their unique contributions to the overall system,

- data processing that focuses on identifying clusters or concentrations of "ordnance" signal returns so that ordnance fields, rather than individual ordnance, are identified.

Detection:

- a ground or near-ground-based platform with integrated-differential GPS for position marking of suspect ordnance to within 50 cm position accuracy,

- magnetic (gradiometric) sensors for surface and buried ferrous-metallic ordnance detection,

- a ground-penetrating radar sensor for detection of ordnance, rocks, voids, and other clutter,

- sensor and data fusion algorithms to assist in exploiting the complementarity between the two sensor types.

Classification:

- a ground-based platform that may operate concurrently with or independently of the detection-stage sensing system,

- a thermal-neutron activation sensor that detects the presence of (at least) nitrogen, a primary constituent of explosive materials.

In addition to identifying the most promising sensor technologies, we have also identified the phenomenology issues that must be addressed for the successful integration and deployment of these sensors. They include

- UXO target signatures as a function of waveband or sensing technique for a broad range of environmental and operating conditions,

- characterization of vegetation and other naturally-occuring and man-made clutter for conditions representative of UXO contamination,

- effects of weather, time-of-day, and foliation on sensor performance,

- statistics of UXO distribution, both tranversely for density and cluster characterization, and vertically for depth of penetration into the soil.

Throughout the document, we have attempted to identify those areas that we feel need to be supported in order to develop a unified strategy for UXO sensing in the United States. Our recommendations have focused on sensor technology development, research requirements to support that development, issues related to the integration of multiple sensors, issues related to data handling and processing, and concerns to be addressed in estimating risks and payoffs associated with our proposed sensing structure. We hope that this document provides SERDP with a useful and timely guide to effectively implementing a research program that can directly enhance the process of site remediation.

# APPENDIX A

## RISK ASSESSMENT MODEL DEVELOPMENT

Two risk-assessment models are needed to support the Government's requirements for the cleanup of unexploded munitions: a public health and safety model to determine the potential risk incurred by public use of a cleaned up site, and a cost/benefit model for Government investment in research and development for UXO detection systems. Clearly, these two models are closely linked. Decisions made on UXO-sensing systems have a significant impact on the health/safety models. The converse is also true. If more risk to the public is allowed, the requirements can be eased on the UXO-sensing system, therefore changing the investment priorities. Figure A.1 shows how requirements flow from the health risk model into the investment model and back to health risk model.

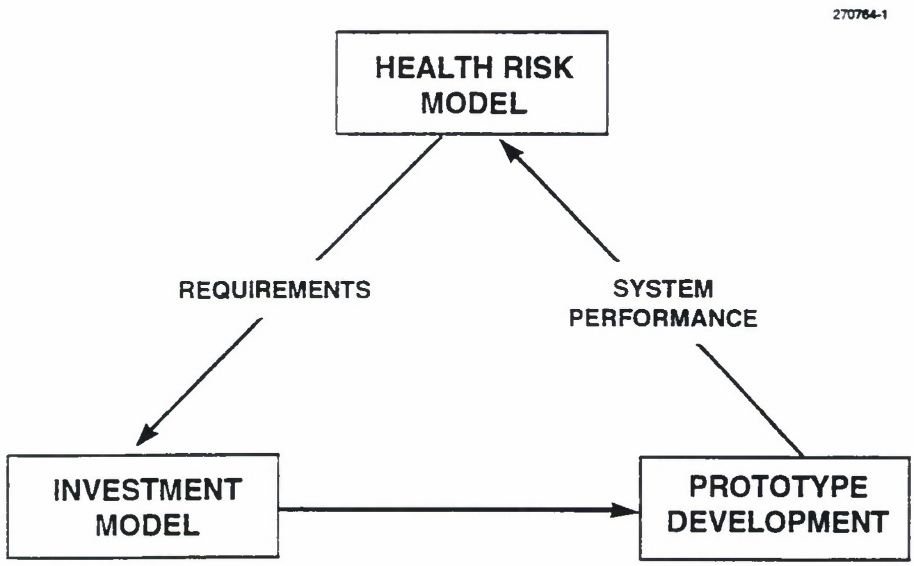


*Figure A.1 Risk-assessment model development process*

## A.1 Health & Safety Risk Model

Developing a public health and safety risk model for land use after a remediation effort requires extensive analysis of the site, the potential munitions, and the UXO system. As it is too early to perform the necessary analysis to construct such a model, this section presents an outline of areas of potential investigation. It is useful to review the steps in building a risk model, as a means of discussing the analysis requirements.

The steps in model development are outlined below.

1. Identify all areas of potential risk and the severity of the risk. The UXO problem has several broad risk categories. These categories include: human injury/death, destruction to property, environmental damage, and public relations. Clearly, there are many sub-categories under each of the categories. In this step the risks from all potential munitions are explored. For example the risk from a deeply buried bomb might be classified as a potential for human injury if the land is used for commercial development, but may be classified as destruction to property if the land is used for grazing.

2. Assign estimated probabilities of occurrence to each of the identified risks. Typically, the probability of occurrence is broken down into broad categories, e.g., frequent, occasional, and remote. Numerical ranges of probability can be assigned to these categories to facilitate Further analysis. Using the example from Step 1, the risk of a deeply buried bomb detonating might be classified as frequent if the site has the potential for excavation. In contrast the same site used for grazing might have a remote possibility assigned to the detonation of the bomb. Another example would have the probability of explosion be a function of depth. Therefore, since the probability of detecting an ordnance is also a function of depth, the overall probability of occurrence would be a very strong function of depth and the detection system. As these examples indicate, the determination of these risks is a function of the overall remediation system design and potential land use.

3. Apply costs to each of the risks. One approach is to apply a monetary cost for each possible outcome. It can be difficult to assign a cost to the injury or death of a person, yet this type of analysis is commonly used in developing risk assessment models for the chemical industry [2]. A more qualitative approach is to assign costs to broad categories such as: catastrophic, severe, serious, and minor. These categories would be assigned simple numeric cost values. For example, four for catastrophic, three for severe, etc.

4. Incorporate the results of the previous steps into the overall model. One approach for quantitatively combining the results is to use an expression similar to the one below.

$$ExpectedCost = P_{occ} \times P_{exposure} \times N_{people} \times Cost \quad [2]$$

where ExpectedCost is the expected safety cost, $P_{occ}$ is the probability of occurrence of a given event, $P_{exposure}$ is the probability of exposure to the risk, $N_{people}$ is the number of expected people exposed, and Cost is an estimate of the cost of the risk derived in Step 3. The probability of occurrence, $P_{occ}$, can be defined as

$$P_{occ} = P_{mun} \times P_{ux}(ordnance) \times (1 - P_d(ordnance))$$

where $P_{mun}$ is the probability that a given type of ordnance is present, $P_{ux}$ is the probability that the ordnance is unexploded, and $P_d$ is the probability that the ordnance would be detected and cleared.

A qualitative approach is to use a risk-assessment code table. A risk assessment code table maps a probability level and a severity level to a risk assessment code (RAC). A sample risk-assessment-code table is shown in Table A.1. The resulting RAC is used to define the amount of risk management that is required. If a qualitative approach is taken, an appropriate table needs to be defined for the UXO problem.

Table A.1
Example risk assessment table

| | Frequent | Occasional | Remote |
|---|---|---|---|
| Catastrophic | 5 | 4 | 3 |
| Severe | 4 | 3 | 2 |
| Serious | 3 | 2 | 1 |
| Minor | 2 | 1 | 0 |

### A.1.1 Recommendation for Model Development

Given the broad outline of the model from above, an effort needs to be undertaken to gather information to develop the model. Typically, this is done by forming a risk-assessment committee. Before a committee is formed it would be useful to gather information on the probabilities described above. A list of necessary data to acquire before a health and safety model can be constructed is given below.

1. probability of exposure versus land use.
2. expected depth versus ordnance type.
3. cost as a function of ordnance.
4. expected hazard life time as a function of ordnance.

Some of this information is currently available; other information can be derived from previous remediation efforts, and the remainder will have to be derived from studies. The probability of detection as a function of ordnance type will not be available until an overall system study is performed. Initially, the probability of detection can be used as a free parameter to derive a set of requirements on the overall UXO remediation system. Once a prototype UXO detection system has been built, the measured probability of detection can be input into the model, and the model can then be used to determine the proper land use.

## A.2 Investment Model

A successful investment model clearly defines the costs and benefits of each option presented. The government can use such a model as the basis for allocating resources to address the UXO problem. In order to provide a basis for constructing an investment model, a preliminary summary is provided at the end of each of the sensing chapters that assesses the research risk, the relative cost, and the benefit of each research recommendation.

The research and development risks are partitioned into three categories. High risk is considered beyond state of the art technology. Moderate risk is considered to be at the state of the art. Low risk is considered commercial-off-the-shelf technology. Development cost is also broken down into the three categories of high ($\$ > 1000$ K), moderate ($1000\text{K} > \$ > 100$ K), and low ($\$ < 100$ k). The payoff category refers primarily to the potential for reduction in remediation costs. A separate analysis should be conducted to assess the risk to human health and safety, since it is possible that a technology that has positive impact on remediation cost may have a deleterious impact on public safety.

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# APPENDIX B

# JEFFERSON PROVING GROUND DEMONSTRATION

## B.1 OVERVIEW OF TEST

"In June 1993, a program was established by the U.S. Army Environmental Center (USAEC), with the U.S. Naval Explosive Ordnance Disposal Technology Division (NAVEODTECHDIV) as the technical lead. The initial phase of the program was an Advanced Technology Demonstration (ATD) project planned and carried out by NAVEODTECHDIV between August 1993 and December 1994. This project included development of a 120-acre controlled test site at the U.S. Army Jefferson Proving Ground (JPG) in Madison, Indiana; solicitation and selection of demonstrators of innovative technology; scheduling and monitoring of demonstrations; and evaluation of demonstration results". [1]

The 120 acre test site at JPG was divided into two areas: a 40 acre test site for ground-based systems, and an 80 acre site for airborne systems. At each site all vegetation 4 inches or less in diameter was cut to a height of approximately 3 inches. Soil probing was conducted to characterize the ground stratification and soil parameters. Magnetometer surveys were conducted to locate magnetic surface debris and magnetic field levels at the site. Magnetic anomalies were also located and a determination was made that the site could be used successfully for the ATD.

The deployment of the targets were made as realistic as possible based on U.S Army data. Listings of the targets and false targets used, and typical depths are given below.

<u>Targets used at JPG site</u>

| | |
|---|---|
| Bombs: | 2000, 1000, 750, 500, and 250 pound. |
| Projectiles: | 8 in, 175, 155, 152, 106, 105, 90, and 76 mm. |
| Rocket warheads: | 5 and 2.75 in. |
| Mortars: | 4.2 in, 81, and 60 mm. |
| Submunitions: | M-42 armor defeating bomblets. |
| Land mines: | TS-50, VS-50 anti-personnel. |
| Aircraft cannon: | 30, and 20 mm. |

<u>Target depths</u>

| | |
|---|---|
| Bombs: | 20 feet or more. |
| Projectiles: | 1 to 12 feet. |
| Rocket warheads: | 3 to 8 feet. |

| | |
|---|---|
| Mortars: | 0 to 4 feet. |
| Submunitions: | on or near the surface. |
| Land mines: | on or near the surface. |
| Aircraft cannon: | on or near the surface. |

<u>False targets</u>
Inert ordnance
Man-made debris
Refilled holes

In addition to the test sites, a "reference site was established to give demonstrators an opportunity to test their sensors against known ordnance at known depths. The following targets were emplaced within the reference site: one 500-pound bomb at a depth of 3.3 m, one 175 mm projectile at a depth of 1.8 m, one 106 mm High Explosive Anti-Tank round at a depth of 1.2 m, and one M-42 armor defeating bomblet at a depth of 0.1 m" [1].

Approximately 30 demonstrators participated in the Phase I test at JPG. Many sensors were deployed including airborne and ground-based, magnetometers, ground penetrating radars, infrared sensors, and electromagnetic-induction sensors. Each demonstrator was allotted 40 hours for data collection, to be completed within a 7 day period. The demonstrators also had to report detections and classifications of the ordnance within that time period. The demonstrators did not have any a priori knowledge of the ground truth.

The detection locations as reported by the demonstrators were compared against the ground truth and scored [1, 2]. A table taken from Reference 1 that summarizes the results of the scoring is shown below. The ground-based magnetometers performed the best and the airborne sensors, including the magnetometer, performed the worst.

Table B-1
UXO ATD JPG — Phase 1 Results

DETECTION RATIOS AND AREA COVERAGE PERFORMANCE BY PLATFORM AND SENSOR TYPES BY CLASSES

| Sensor Type | Transport Modes | Overall Detection Ratio | Ordnance Detection Ratio | Search Coverage | Number in Class |
|---|---|---|---|---|---|
| GPR | Air | 1% | 1% | 79% | 3 |
| Infrared | Air | 8% | 7% | 100% | 1 |
| Magnetometer | Air | 4% | 4% | 100% | 1 |
| Multi-sensor | Air | 1% | 1% | 100% | 1 |
| Multi-sensor | Ground-Multimodal | 24% | 25% | 71% | 3 |
| Magnetometer | Ground-All Modes | 33% | 30% | 69% | 11 |
| Magnetometer | Ground-Multimodal | 40% | 40% | 95% | 4 |
| Magnetometer | Ground-Handheld* | 23% | 20% | 64% | 7 |
| Magnetometer | Ground-Vehicular | 65% | 59% | 29% | 1 |
| GPR | Ground-All Modes | 8% | 9% | 21% | 6 |
| GPR | Ground-Vehicular | 7% | 7% | 24% | 5 |
| GPR | Ground-Handheld* | 14% | 20% | 4% | 1 |

* Handheld or Man-Towed

## B.2 EVALUATION OF JPG ATD

In evaluating the JPG test it is important to remember that it was an Advanced Technology Demonstration. A realistic scenario was prepared and various technologies brought to bear. Considering the claims that have been made in recent years concerning the abilities of certain technologies to detect deeply-buried objects an ATD was the appropriate response. The failure of these technologies to perform in the advertised manner is simply a reality check.

Nonetheless, it is useful to critique the JPG effort lest anyone draw too many conclusions from the overwhelmingly negative results. Here are the main points of criticism:

1. The demonstrators did not report on the methodologies used for calibration, processing, detection, and classification (if performed).

2. The demonstrators may not have had ample time or may not have been the appropriate parties to apply advanced detection algorithms to the data.

3. No system analysis was performed to determine whether the sensors that participated should have detected the targets.

4. All sensors were evaluated in the same way. Since magnetometry is a fundamentally different technology than GPR, the physics of the detection process for each sensor is different. Each technology should be evaluated in a domain that systems analysis supports. The evaluation methodology was unfairly biased to the technology that coincided with the deployments used.

## B.3 RECOMMENDATIONS

A very considerable effort was expended to execute the JPG test. There is a large amount of sensor data that was collected by the demonstrators that hasn't been amassed into a central database. This is also true of the soil measurements. It is almost certain that the data has not been fully exploited and analyzed. It would be worthwhile to have a research laboratory (or other technically-qualified organization) investigate this data set to study the fundamental technologies, model the phenomenology, and perform detection studies. The laboratory would need to be provided with the ground truth to perform the above analyses. The result of such an effort would be an independent assessment of the capabilities of the participating technologies to detect UXOs in the JPG scenario based on the underlying physics. Recommendations could be made as to how to improve detection performance by understanding the optimal performance of each sensor technology.

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# APPENDIX C

# REMOTE MINEFIELD DETECTION SYSTEM (REMIDS)

## C.1 System Overview

The Remote Minefield Detection System (REMIDS) is a helicopter-borne, surface-mine detection system utilizing passive long-wave infrared sensors and a laser-imaging system. It is being developed at the Waterways Experimental Station (WES) Coastal Engineering Research Center Laboratory, Vicksburg, Mississippi. (References 1-11 provide detailed information on REMIDS and supporting programs). REMIDS utilizes surface reflectance and polarization of the return signal from surface mines illuminated by a 1 μm line-scanning laser in conjunction with a thermal IR sensor operating in the 8 - 12 μm band.

The primary objective of the REMIDS system is surface-mine detection. It operates primarily in conditions with unobscured views to the mine location, that is, without foliage or surface water. The sensor utilizes a line scanning 1 μm laser and records horizontal and vertical polarization. Detection is based on real-time analysis of the degree of polarization and the imagery from the co-aligned scanning thermal IR sensor operating in the 8 - 12 μm band.

REMIDS was evaluated at the Standoff Minefield Detection System Advanced Technology Transition Demonstration in FY 90 and 91. The following section is a brief description the test results.

## C.2 REMIDS at the Standoff Minefield Detection System Advanced Technology Transition Demonstration

The Remote Minefield Detection System (REMIDS) along with four other mine detection systems participated in the Standoff Minefield Detection System (STAMIDS) Advanced Technology Transition Demonstration (ATTD) in FY 90 and 91. The purpose was to demonstrate the maturity and capability of a variety of Standoff Mine Detection (SMD) systems. The STAMIDS ATTD objectives centered on detecting surface-laid minefields, detecting minefield boundaries, and determining if any of the SMD systems could locate buried minefields.

The participants in the STAMIDS ATTD were

1. REMIDS - a helicopter-borne system comprising an active laser (1.06 μm) and a passive LWIR (8 - 12 μm) sensor. The laser system collected reflectance and polarization image data; the LWIR system collected thermal emission data. This system includes a real-time image and data-analysis system that automatically detects mines and minefields.

2. Airborne Minefield Detection and Reconnaissance System (AMIDARS) - a passive IR sensor system relying on thermal images for detection developed by the US Army Belvoir Research and Engineering Center. This system did not have real-time data analysis capability. This system flew on a fixed wing aircraft.

3. CounterMine Airborne Detection and Surveillance (CMADS) - a helicopter-borne passive IR sensor system relying on thermal images for detection developed by the Martin Marietta Missile System Corporation. This system did not have real-time data analysis capability.

4. Airborne Mine Detection and Surveillance (AMDAS) - an active laser system flying on a fixed wing aircraft that forms images using the reflected laser light. This system did not supply detection information for evaluation.

5. Digital On-line Recording and Image Processing System (DORIS) - a multi-spectral imaging system developed for the German government by the Dornier Corporation. Mine detection was performed by visual inspection of the multi-spectral imagery. This team did not submit detection reports for independent evaluation.

Table C.1 provides the area coverage information for each of the SMD systems.

Table C.1
Area Coverage for Three STAMIDS ATTD Participants

| System | Ground Swath (m) | Altitude (ft) | Airspeed (knots) |
|---|---|---|---|
| REMIDS | 30<br>50 | 130<br>200 | 35<br>35 |
| AMIDARS | 300<br>350 | 750<br>1000 | 75<br>75 |
| CMADS | 20<br>30 | 400<br>500 | 40<br>40 |
| AMDAS | 21 | 900 | – |
| DORIS | 600 | 600 | – |

The STAMIDS ATTD had two phases. Phase I occurred at Fort Hunter Leggett (FHL), California site that contained large areas of terrain suitable for tanks. FHL is a semi-arid, and at the time drought-stricken, environment. Phase II occurred at Fort Drum, New York, which was selected for its temperate conditions, moist environment, and highly vegetated background.

A comprehensive set of observations was taken with each system. A broad selection of mines and mine placements was observed, the diurnal effects of thermal signatures were addressed, and some opportunity to optimize the systems was provided. Detailed summary reports for both phases are available. The primary results are

1. Only the REMIDS exhibited a high probability of detection (Pd) for surface-laid minefields.

2. The thermal imaging systems (AMIDARS and CMADS), which rely on thermal variations, performed best during daylight transition periods (dawn and dusk). REMIDS was unaffected by time of day.

3. The lowest Pd occurred in the scattered-tree background. This result is expected, since the foliage and grasses in the area obstructed the mines.

4. REMIDS real-time system performed well. It provided minefield detection within a two-hour, post flight report period.

5. The level of a priori information affected the performance of the thermal imager. In Phase I, algorithms were used that assumed a level of soil moisture that was not present.

6. Each system showed some promise in locating buried minefields.

Table C.2 is a very high-level summary of the STAMIDS ATTD. The probability of detection for minefields as a function of time of day is listed. The composite average overall times are also provided. It is important to note that the REMIDS system was relatively insensitive to time of day; wheras the two thermal imaging systems performed best at dawn and dusk. It is also important to point out that these results indicate the detection rates for minefields, not individual mines.

Table C.2
Minefield Detection Summary for the STAMIDS ATTD

**System Probability of Detection**

| | Morning | Daytime | Evening | Nighttime | Composite |
|---|---|---|---|---|---|
| REMIDS | 72.4 | 89.6 | 81.0 | 80.5 | 80.4 |
| AMIDARS | 25.0 | 58.1 | 61.0 | 21.9 | 39.4 |
| CMADS | 68.7 | 68.7 | 70.7 | 51.7 | 56.5 |

Table C.3 summarizes the ability of each of the systems to recognize minefields as a function of placement. In this case, the minefield detection is tabulated in terms of minefield type, conventional surface-laid, scattered, or buried.

Table C.3
Minefield Detection Summary for the STAMIDS ATTD

**System Probability of Detection (%)**

| | Conventional | Scatterable | Buried |
|---|---|---|---|
| REMIDS | 98.9 | 66.3 | 34 |
| AMIDARS | 65.0 | 10.0 | 2.4 |
| CMADS | 87.4 | 18.9 | 12 |

## C.3 Applicability of REMIDS for UXO-Sensing

Based on the results of the STAMIDS ATTD a few comments can be made with respect to sensing UXOs.

1. The results of the STAMIDS ATTD can be applied to the detection of UXO sites, as opposed to individual UXOs. The ability of the system to located scattered or buried minefields is indicative of the ability of the system to locate sites with surface or near-surface UXOs. The resolution of the instrument (3 inches from 200 ft altitude) should be capable of providing specific location of targets, though this was not specifically addressed in the STAMIDS ATTD.

2. The good performance of REMIDS compared to the two passive systems seemed largely to be the result of its active component. For UXO sensing in vegetated areas, the system effectiveness could be improved if additional wavelengths were added that caused fluorescence in the foliage, thereby providing a unique clutter-identification signal.

3. An additional LWIR band might enhance the ability to differentiate between surface-temperature variations and emissivity variations, thereby increasing the probability of detection. An even superior sensing alternative would be a hyperspectral imager. The benefit would be increased spectral diversity, perhaps some improved foliage penetration, and an increased feature set on which to base discrimination algorithms.

4. REMIDS was developed for a tactical environment that has a real-time processing requirement. REMIDS met their timeliness requirements during the STAMIDS ATTD and we suggest that the real-time feature be preserved for applications related to UXO sensing.

5. The effect of a priori environmental conditions must be included in the detection and discrimination algorithms. Field measurements across a broad range of environmental and meteorological conditions need to be taken.

6. Although REMIDS showed the most promise of each of the tested systems, it relied on visual interpretation of thermal images for buried mines. For real UXO-sensing scenarios, we suggest that automatic target recognition algorithms be developed for buried-object detection.

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# APPENDIX D

# MOBILE UNDERWATER DEBRIS SURVEY SYSTEM (MUDSS)[1]

## D.1 Background

The MUDSS program is a recently funded (as of 1994) effort to demonstrate technologies neccessary for underwater surveys of shallow waters littered with ordnance. The program is a three-year, $4 million effort being conducted jointly by the Naval Surface Warfare Center, Coastal Systems Station (CSS) and NASA's Jet Propulsion Laboratory (JPL).

The objective of MUDSS is to demonstrate sensor and processing capabilities that enable the detection and classification of proud and buried underwater ordnance and the discrimination of ordnance from false targets such as rocks, seashells, and man-made debris. The program heavily leverages investments in mine-detection and signal processing technologies developed at CSS and sensor fusion and visualization technologies developed at JPL for various applications.

The approach that the researchers have taken to achieving their objectives is the development of a trailerable multi-sensor suite of instruments that offer complementary capabilities for underwater detection, classification, and identification. (Note that these terms are used somewhat differently in the underwater-survey community than in our document). Figure D.1 displays examples of an underwater scene interrogated by various sensors in the different categories. Detection is achieved, for example, by a low-frequency sonar that is used to search a wide area for regions of enhanced signal return. The resolution in this mode is poor, and the signal returns appear as bright spots on the sonar displays. The position information of those bright spots is then used to interrogate the suspected targets with the classification sensor, typically a higher-frequency sonar. Usually, the classification-sonar resolution is high and permits classification of targets by their shape. For example, an elongated bomb could be distinguished from a circular mine. Finally, in order to positively identify the object, an even higher resolution sensor, such as a laser-based imager, interrogates the target. Two other sensor types are included in the MUDSS program: a gradiometer is used as a classification sensor for ferrous targets and a chemical sensor is planned for identification of explosive compounds.

## D.2 Task Descriptions

The MUDSS program has defined four primary tasks [1]:

---

[1] For information on MUDSS contact: Coastal Systems Station @ (904) 234-4231 or Jet Propulsion Laboratory @ (818) 354-8614

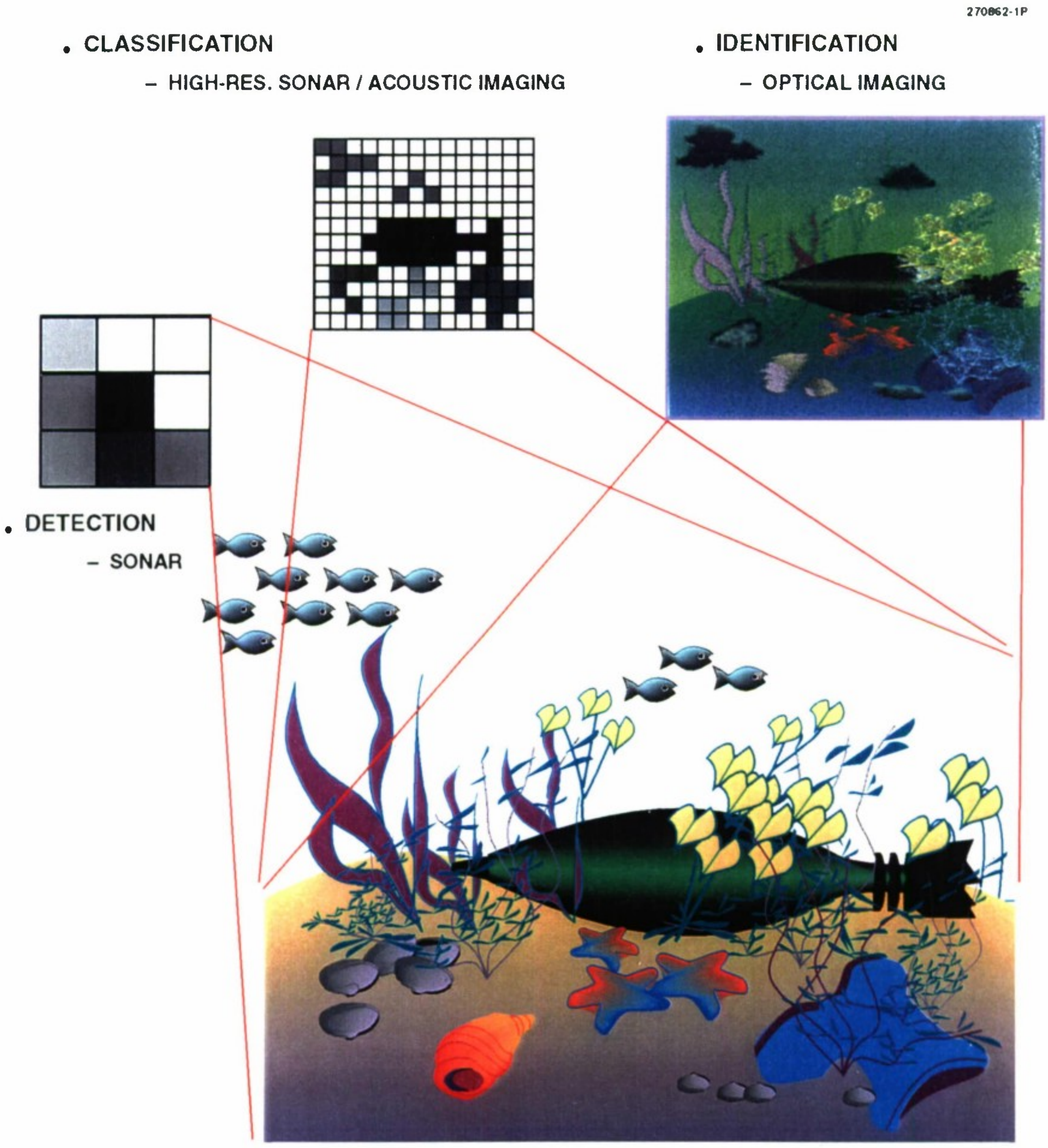


*Figure D.1* *Example of underwater scene viewed with detection, classification, and identification sensor types.*

Task 1: Sensor suite adaptation and integration

The main objectives of this task are to modify existing sensors that have been developed for other programs and to integrate them into a sensor suite capable of

- high-resolution, acoustic imaging of proud or shallowly buried ordnance in shallow water at ranges up to 50 m,
- high-resolution optical imaging of proud ordnance at ranges up to seven attenuation lengths
- multi-target magnetic localization of buried and proud ordnance at ranges up to 50 m, and
- short-range chemical detection of explosives.

Both magnetic and acoustic mine detection were addressed in CSS's Magnetic/Acoustic Detection of Mines (MADOM) developmental program, which ended in 1990. [2,3] A follow-on technology development effort (Mine Reconnaissance/Hunter or MR/H program) [4] is underway at CSS for very-shallow water-minehunting. The optical imaging is performed with a laser-line scanner developed by ART, Inc.. The chemical sensor was developed by JPL and is called the Mass Spectrometer Explosives Detector (MSED).

Task 2: Automatic target receognition processor (ATRP) development

The task objective is to develop a high-speed (~200 Mbit/s) ATRP for MUDDS sensor suite operation, automatic target detection and classification, and 3-D visualization of fused-sensor data in a noisy and cluttered background. The approach is to modify and improve existing CSS-developed automated acoustic and magnetic target classification routines, develop ordnance morphological-classification routines, design and build a COTS-based sensor operation system and processor, and test classification routines both offline during a feasibility demonstration (FD) and in real time during a technology demonstration (TD).

Task 3: Data fusion and visualization tools development

The objective is to develop a near real-time, dynamic, 3-D visualization capability to maximize operator understanding of the multi-sensor data. Prototype visualization and fusion tools for the MUDSS sensor suite will be developed and tested during the FD; they will be refined and exercised during the TD. JPL is developing both a Site Survey Tool and a Site Remediation Planning Tool. The function of the former is to provide guidance information to the MUDSS platform vessel; navigation and chart information will be used to plot survey-area boundaries. The Site Remediation Planning Tool will be used to review the data gathered by the individual sensors, apply (where appropriate) aided-target-recognition algorithms to the data, and overlay the processed data on topographic displays of the sea floor.

Task 4: Platform system development, systems engineering, and demonstration

The task objectives are to develop a trailerable, single-unit catamaran platform for MUDSS, perform the prototype and TD system integrations, and execute the feasibility and technology demonstrations. The approach is to initially procure a low-cost, commercially available, non-magnetic vessel to deploy the MUDSS sensors and to house the data-acquisition system; this vessel would be used in the FD. Eventually, a specially-made non-magnetic catamaran would be built and the final sensor and data acquistion would be integrated for the TD.

## D.3 The Feasibility Demonstration

A feasibility demonstration was completed in September 1995, in which two dozen targets were placed at a depth of 30 feet on the bottom of St. Andrew Bay, Panama City, FL. [5] The targets ranged in size from 60 mm mortar shells to 2000 lb. bombs and 55 gallon oil drums. A trailerable sensor suite was deployed from a shallow-water, nonmagnetic vessel; the depth of the sensors below the craft was winch controlled. Data were acquired from multiple passes over the target fields with various combinations of sensors operational (including several runs with all sensors operational). The sensor characeristics included in the FD are summarized in Table D.1.

Table D.1
Sensor types and features used in the MUDSS feasibility demonstration

| | | |
|---|---|---|
| Ahead-look sonar (Sea Bat) | 455 kHz | 90° f-o-v |
| Low-frequency synthetic aperture sonar (SAS) | 20 kHz | Resolution 7.5 cm x 7.5 cm |
| High-frequency SAS | 600 kHz | 5 cm x 5 cm |
| SQUID Gradiometer | Ferrous target localization | |
| Electro-optic sensor | Laser linescanner | 6 mm x 6 mm |

Although the final report describing the results of the feasibility study was not yet available at the time of this writing, we were able to speak with researchers involved in the demonstration. [5,6,7] All targets were visible and identifiable to the sensor suite. It is not clear, without reviewing the data, if any of the sensors were redundant or if all were required to positively identify every target. Although some sensor functions are redundant, factors such as commercial availablity, ease of interpretation, or ease for retargeting may ultimately dictate the optimum sensor combination. From some example images that we have seen and from discussions with personnel involved, it appeared that even the smallest targets examined were visible to the two SAS systems. The gradiometric data seemed to offer more of a confirmation of SAS classification than new information. (Since none of the targets were buried, the true potential utility of the gradiometric sensor was not exploited). The laser linescanner offered impressive visual imagery of the targets it examined.

## D.4 Technical Assessment of the MUDSS System Concept

It is difficult to critically review a program based solely on its original proposal, conversations with researchers, and summary high-level brochures describing system characteristics and performance. Nevertheless, because much of the technology deployed so far was developed under other programs for which considerable information is available, such as MADOM, we can make a preliminary assessment.

In general, we feel that the MUDSS program is a well-constructed, worthwhile effort to design a survey system for underwater UXO that will be relevant in most of the 50 or so underwater FUD sites suspected of contamination. The sensor suite chosen for the feasibility demonstration seems appropriate, especially since much of the development effort had been conducted for previous programs. The feasibility demonstration itself served as an early opportunity to assess the performance of the sensors, as well as to acquire some characteristic signature data on representative ordnance targets.

We do feel that the feasibility demonstration could have been strengthened by a couple of additional measurements. First, only proud targets were examined yet the principal rationale for deploying the gradiometer (and, to some extent, the low-frequency SAS) is the potential for detecting buried ordnance. Thus, it is not clear that enough is known from the feasibility demonstration to adequately define the sensor requirements for the technology demonstration, which will presumably include a subset of buried targets. Second, the area where the ordnance were placed was apparently heavily littered with natural and man-made clutter. The area was thoroughly mapped prior to target placement, however, and the clutter was effectively zeroed out of the subsequent measurement set. Although this is not an unreasonable method for testing sensor probability of detection, it offers little insight into false-alarm rate, which is an important component of the total system design. We suggest that some additional, more stressing measurements be conducted prior to the actual technology demonstration, to assist in overall design decisions.

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MIT Lincoln Laboratory has been tasked, by the Strategic Environmental Research and Developmental Program (SERDP), to assist in defining basic and exploratory research and development needs in the area of unexploded ordnance (UXO) sensing. Recently completed is a four-month study recommending and supporting the evaluations documented in this report. Recommended is a systems approach to UXO sensing that emphasizes the

- Utilization and integration of existing sensing technologies
- Investigation of phenomenological concerns associated with different sensors, environmental conditions, and UXO types
- General requirements on data handling, processing, and interpretation

Defined is a structure in which to initiate and conduct UXO-sensing technology development and, where possible, recommendations have been supported with analyses and examples from related sensing applications. These recommendations are intended to serve as a guideline for SERDP in establishing its future research priorities for the challenging task of characterizing and remediating UXO-contaminated lands in the United States.

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